Improving Shipboard Maintenance Practices Using Non-Intrusive Load Monitoring

by

Mark A. Piber

B.S., Naval Architecture and Marine Engineering
United.States. Coast Guard Academy, 2003

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the
Requirements for the Degrees of
Master of Science in Naval Architecture and Marine Engineering
and
Master of Science in Mechanical Engineering
at the
Massachusetts Institute of Technology

June 2007

Signature of Author ______________________________
Department of Mechanical Engineering
May 11, 2007

Certified by ______________________________
Steven B. Leeb
Professor of Electrical Engineering and Computer Science & Mechanical Engineering
Departments of Electrical Engineering and Computer Science & Mechanical Engineering
Thesis Advisor

Certified by ______________________________
Robert W. Cox, Assistant Professor
Department of Electrical and Computer Engineering
University of North Carolina at Charlotte
Thesis Advisor

Accepted by ______________________________
Lallit Anand, Professor of Mechanical Engineering
Chairman, Department Committee on Graduate Students
Department of Mechanical Engineering

Page Intentionally Left Blank

Improving Shipboard Maintenance Practices Using Non-Intrusive Load Monitoring

by
Mark A. Piber

Submitted to the Department of Mechanical Engineering on May 12, 2007 in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Naval Architecture and Marine Engineering
and
Master of Science in Mechanical Engineering

Abstract

The Non-Intrusive Load Monitor (NILM) is a device that utilizes voltage and current measurements to determine the operating profile and individual loads on a system from a single aggregate measurement. The NILM can also be used to actively monitor and quickly diagnose system failures or improper operation. Current NILM research conducted at Massachusetts Institute of Technology's Laboratory for Electromagnetic and Electronic Systems (LEES) is exploring the application and expansion of NILM technology for the use of monitoring shipboard systems.

This thesis presents the implementation of the NILM on a vacuum aided sewage collection system, a ship's service low pressure compressed air system, and a vane axial ventilation supply fan. The NILM's ability to the monitor the power usage profile of these systems could be used to immediately diagnose system casualties and unusual operation parameters. Measurements and experimentation were conducted onboard the *USCGC ESCANABA (WMEC-907)* and the *USCGC SENECA (WMEC-906),* 270-foot Coast Guard Cutters home ported out of Boston Harbor.

New casualty parameters were recorded and analyzed in an attempt to verify and expand on diagnostic software currently being developed for the vacuum aided sewage collection system. The analysis of the ships service compressed air system provides an example of what immediate diagnostics such software would be able to provide for the user. Additional analysis of a misaligned ventilation fan provides evidence of the NILM's ability to constantly monitor steady state systems. The expansion of testing onto the *ESCANABA* provides valuable verification of previous data collected onboard the *SENECA* during past research.

Thesis Advisor: Steven B. Leeb
Title: Associate Professor of Electrical Engineering and Computer Science

Acknowledgements

The author would like to acknowledge the following organizations and individuals for their assistance. Without them this thesis would not have been possible.

- The Office of Naval Research's Control Challenge, ONR/ESRDC Electric Ship Integration Initiative and the Grainger Foundation, all of whom provided funding
- LT Greg Sabra and LT Jen Haag for their support onboard *USCGC Seneca* and *USCGC Escanaba.*
- Jim Paris and Chris Laughman for their computer and NILM technical assistance
- Steve Leeb for pulling me into the type of research that will help me throughout my career. I'm sure his gadgets will follow me during the same time period as well.
- Rob Cox for his excellent guidance throughout my research coupled with the uncanny ability to know when I'm actually busy or just being lazy. He also laughed at all my jokes and that's important.
- And finally Warit Wichakool for his patience and magical gadgetry skills. Without his guidance and unwavering willingness to check over my work at a moment's notice I wouldn't have been able to write this thesis at all. For that I am truly thankful.

Table of Contents

List of Figures

List of Tables

Page Intentionally Left Blank

1 Introduction

1.1 Motivation of Research

Modern warships face a number of rapidly changing requirements. There is constant pressure to reduce manning, maximize readiness, and decrease maintenance costs. There is also an intense desire to increase operating tempos, forcing maintenance providers to make repairs faster and to ensure that equipment operates reliably for longer periods [23].

To meet the rapidly changing requirements of modern naval vessels, it is necessary to continuously monitor the state of critical machinery systems. The Navy's Integrated Condition Assessment System (ICAS) and the Coast Guard's Main Propulsion Control and Monitoring System (MPCMS) installed on the 270' Famous Class Cutters have been developed to enable the necessary monitoring capabilities. Both use sensor data to assess the status of critical systems and to provide operators and maintainers with the information needed to take action at the optimal time [1]. One drawback of ICAS and other similar systems is that they require individual devices to be independently monitored by a number of different sensors (i.e. RTDs, tachometers, accelerometers, etc.). Some estimates indicate that ships in the DDG-1000 class may have as many as 200,000 sensors [2]. Although such a large sensing network can be advantageous, it is also expensive and difficult to maintain. As the age of the warship increases, an increased dependence on watch standing usually occurs when non-vital monitoring systems are not kept fully operational. A simple, low-cost alternative with lower sensor density could increase reliability and enhance the capabilities of existing systems.

One device that can simplify the monitoring and assessment process is the non-intrusive load monitor (NILM). The NILM, which measures the current and voltage at one or more central locations in a power-distribution network, can determine both the operating schedule and the operational status of each of the major loads in an engineering plant [3] [4]. In many cases the NILM can also use electrical data to assess the status of certain mechanical elements such as flexible couplings, valves, and filters [5] [6] [7] [8]. Because a NILM-based monitor greatly reduces the number of required sensors, it can decrease costs and increase the effectiveness of organizational-level maintenance.

1.2 NILM Overview

Figure 1-1 shows the block diagram of a standard NILM. Note that the NILM measures the aggregate current flowing to a bank of electrical loads. It then disaggregates the operating schedule of individual loads using signal-processing techniques [23]. In an engineering plant, the candidate installation locations include generator output busses and distribution panels.

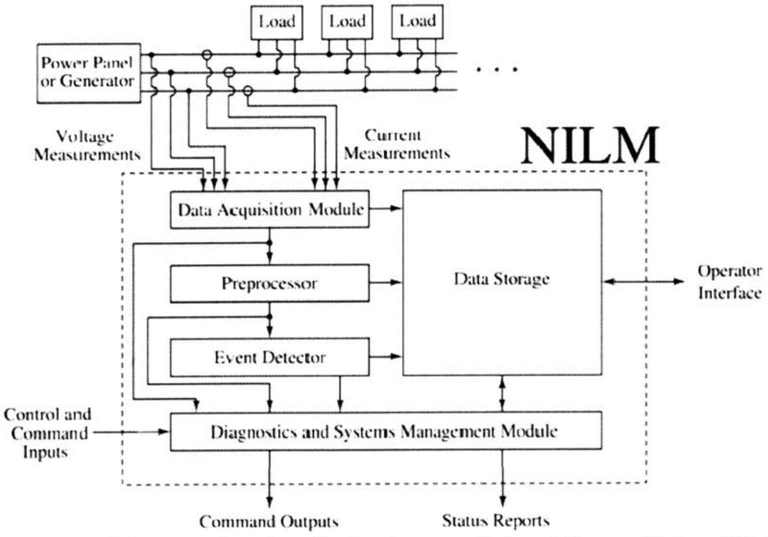


Figure 1-1: Diagram showing the fundamental signal flow path in a NILM

Using measurements of the line voltage and aggregate current, a software-based preprocessor onboard the NILM computes time-varying estimates of the frequency content of the measured line current [4]. Formally, these time-varying estimates, or spectral envelopes, are defined as the quantities [9]

$$a_m(t) = \frac{2}{T}\int_{t-T}^{t} i(\tau)\sin(m\omega\tau)d\tau \tag{1}$$

and

$$b_m(t) = \frac{2}{T}\int_{t-T}^{t} i(\tau)\cos(m\omega\tau)d\tau\,. \tag{2}$$

These equations are Fourier-series analysis equations evaluated over a moving window of length T [10]. The coefficients $a_m(t)$ and $b_m(t)$ contain time-local information about the frequency content of $i(t)$. Provided that the basis terms $\sin(m\omega\, t)$ and $\cos(m\omega\, t)$ are synchronized to the line voltage, the spectral envelope coefficients have a useful physical interpretation as real, reactive, and harmonic power [3].

The spectral envelopes computed by the preprocessor are passed to an event detector that identifies the operation of each of the major loads on the monitored electrical service. In a modern NILM, identification is performed using both transient and steady-state information [11]. Field studies have demonstrated that transient details are particularly powerful because the transient electrical behavior of a particular load is strongly influenced by the physical task that is performed [3]. As shown in Fig. 1-2, for example, the physical differences between an incandescent lamp and an induction machine result in different transient patterns. Figure 1-3 demonstrates the positive identification of an induction motor driving a small vacuum pump. Further details of the detection and identification process can be found in Lee [11] and Leeb [3].

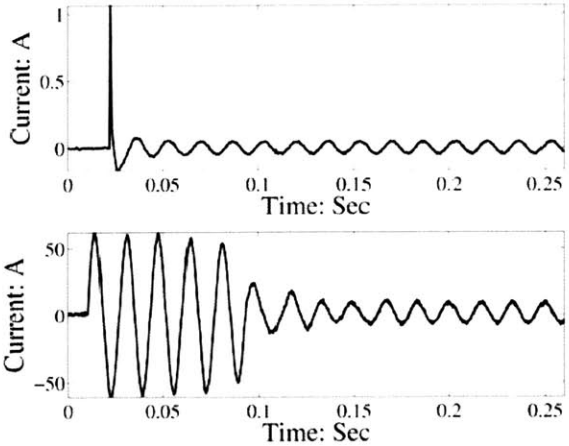


Figure 1-2: Top trace: Current drawn during the start of an incandescent lamp. Bottom trace: Stator current drawn during the start of an unloaded, fractional horsepower induction machine[23].

The final block in Fig. 1-1 is the NILM's diagnostics and systems management module. This software unit assesses load status using any required combination of current data, voltage data, spectral envelopes, and load operating schedules [12]. The successful application of this module has been demonstrated in numerous publications eg., [4], [6] [8], [11], [16]. Shipboard applications are highlighted in [5], [6],[8], and [14].

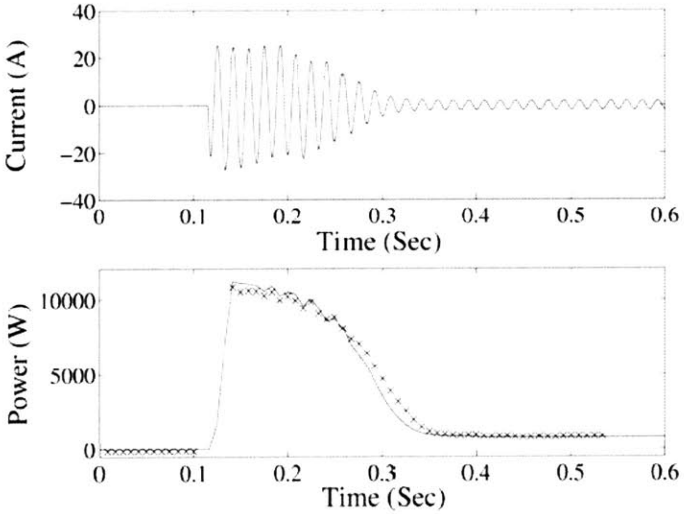


Figure 1-3. Measured current and computed power during the start of 1.7hp vacuum pump motor. Also shown in the power plot is a section of the template that has been successfully matched to the observed transient behavior by the NILM's event detector[23].

As shown in Fig. 1-1, the NILM is designed to interact with human or automated devices in a number of different ways. For instance, the NILM can use its diagnostic information to command certain loads to either commence or cease operations. Additionally, the NILM can provide regular status reports to human operators. To assist in future maintenance operations, the NILM stores all of the relevant data streams (i.e. currents, voltages, operating schedules, etc.) in either a local or remote database [17]. The NILM's vast storage capabilities make it possible for the operator to perform historical data trending. Note that this off-line analysis can be conducted on a remote PC using convenient software packages such as Microsoft Excel [17]. The following sections describe how these capabilities can be used to prevent or detect certain critical shipboard faults.

1.3 Objectives and Outline of Thesis

The research presented in this thesis is a continuation of research conducted by LCDR Jack S. Ramsey, Jr. [19] , USN, LT Thomas W. DeNucci, USCG [18], and LT James P. Mosman, USN [20]. LCDR Ramsey introduced the program onto several marine platforms to determine the feasibility of monitoring shipboard systems with the NILM. Following Ramsey's positive results, LT DeNucci and LT Mosman expanded research by developing diagnostic tools to monitor the health of several fluid systems including the auxiliary sea water system (ASW), sewage collection hold and transfer system (CHT), and reverse osmosis water purification system. All data collection and experimentation for their preliminary research was conducted onboard the *USCGC Seneca*, a 270' Famous Class Coast Guard Cutter.

To confirm results of the earlier work, the research presented in this thesis was performed on identical systems onboard the *USCGC Escanaba*, a sister ship with a similar operational profile. Both of these operational units use the MCPMS to monitor only one or two diagnostic parameters for each Auxiliary System, and those parameters are usually only indicators of gross system failure (i.e. low pressure, high level alarms, etc). Hourly watch-stander observations are currently the only way to monitor all of the parameters needed to completely assess auxiliary system health. The work presented in this thesis demonstrates that the NILM can successfully detect many minor system failures that can lead to more serious system casualties.

This thesis focuses on results that demonstrate how the NILM can detect many common faults simply by examining the operating schedule of the appropriate electrical loads. These loads include a vacuum-assisted sewage collection system, a low pressure compressed air system, and a vane axial ventilation fan. Emphasis is placed upon three sets of normal conditions, namely cycling-system leaks, pump faults, and controller and sensor failures. Chapter two focuses on the several mechanical and electrical failures that can be diagnosed on the sewage collection, hold, and transfer system (CHT). Chapter three examines a compressed air system to give an example of the NILM's universal applicability and the ability of software to provide relevant system feedback. Chapter four introduces the NILM's ability to examine frequency content of a load to possibly be able to detect imbalance on a vane axial fan. Each section includes a description of the system and relevant field examples.

2 Collection Hold and Transfer (CHT) Sewage System

2.1 Introduction

The CHT system has been of great interest since the inception of NILM research with the USCG. The system on the *USCGC Seneca* was first monitored by Ramsey and was investigated and modeled in depth by Mosman. This previous research focused on the feasibility of NILM usage on the system [19] followed by creation and validation of statistical diagnostics [20]. This thesis focuses on the installation of the NILM onboard the *USCGC Escanaba* and the new diagnostic parameters observed by the NILM on both test platforms. This work builds upon the diagnostic tools developed by Mosman and introduces new concepts based on fault conditions that were previously unobserved.

2.1.1 General Description of System

The Collection, Hold, and Transfer (CHT) Sewage System consists of piping, tanks and pumps that creates a vacuum to facilitate the collection and storage of waste from twenty one locations located throughout the ship. The system is located in the Auxiliary Machine Space (AMS) onboard the 270' Famous class cutters and is considered one of the more vital components of shipboard habitability. A basic physical diagram of the system can be seen in Figure 2-1.

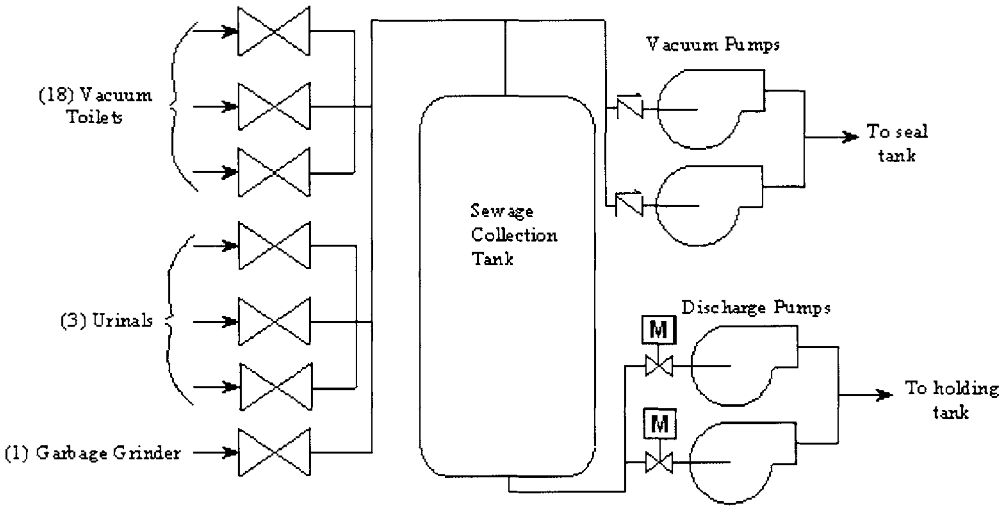


Figure 2-1: Basic Physical Diagram of the Sewage Collection System [20]

Figure 2-2: ***USCGC Seneca*** **(left) and a picture showing the two CHT vacuum pumps and 360 gallon vacuum collection tank or VCT (right) [20].**

Central to the system is a 360 gallon sewage collection tank usually referred to as the Vacuum Collection Tank (VCT). Two alternating vacuum pumps energize and evacuate the air from the VCT upon reaching a low vacuum pressure and de-energize upon reaching a high vacuum pressure once the system has been "charged". Two alternating discharge pumps energize upon a high liquid level in the tank and de-energize upon reaching a low level after all liquid sewage has been transferred to a larger storage tank. Two check valves isolate the vacuum pumps from the collection tank when they are not in operation while two motor actuated valves isolate the discharge pumps. Usage lines from around the ship enter the tank at the top and can be isolated by local valves in the space. Control of the system is achieved by a local control panel that receives electrical signals via pressure switches and probes which serve to monitor the vacuum pressure and liquid levels inside the tank. Typical parameters for the CHT systems found onboard 270' Famous class cutters such as the *Seneca* and *Escanaba* can be seen in Table 2-1 below [21]. A general control diagram can be seen in Figure 2-3.

Table 2-1: CHT System Parameters and Loads [20]

Parameter	Value
High Vacuum (P_0)	18 in-Hg
Low Vacuum (P_{low})--1 pump starts	14 in-Hg
Lower Vacuum (P_{lower})--2 pumps start	12 in-Hg
Vacuum Pump Capacity (each)	23 cfm @16 in-Hg
Discharge Pump Capacity (each)	30 gpm
Holding tank capacity	360 gallons
System capacity (approx.)	600 gallons
System Loads	
(18) Vacuum Toilet Assemblies	≈0.375 gal per flush
(3) Vacuum Urinal Assemblies	≈0.25 gal per flush
(1) Garbage Grinder Kit	≈0.83 gal per use

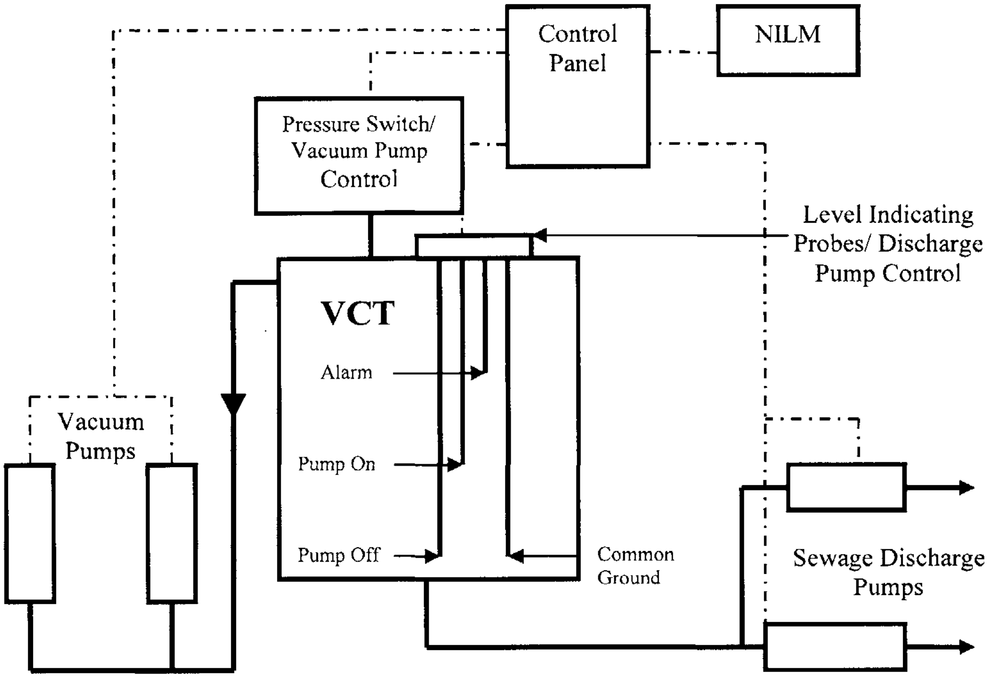


Figure 2-3: Basic System Control Diagram Including NILM. Solid lines indicate air and sewage paths while dashed lines indicate electrical connections.

Onboard the Escanaba and the Seneca, the NILM monitors the power consumed by all four pumps in the system. This data is compiled into hour long blocks and stored for later review. A typical power trace from the CHT system can be seen below in Figure 2-4:

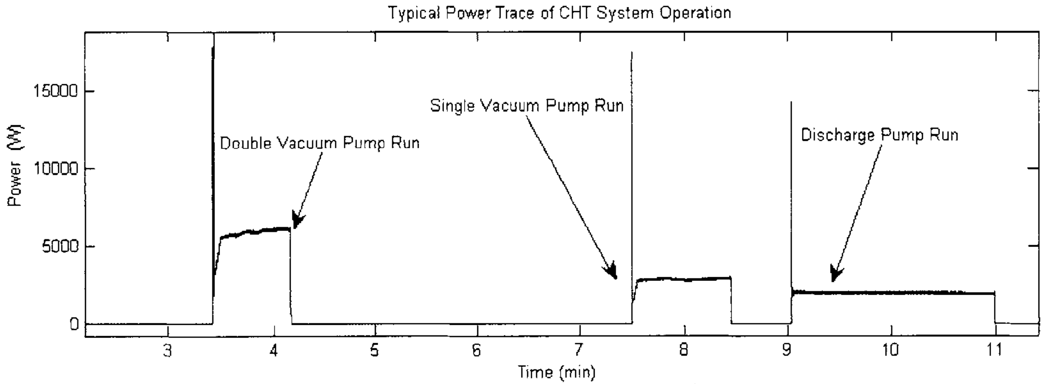


Figure 2-4- Typical Power Traces Associated with the CHT System.

Figure 2-4 presents the three power signatures typically observed during normal operation. These signatures, each of which is indicated in the figure, are the following:

1. Double Vacuum Pump- This run occasionally occurs when the pressure in the tank suddenly drops below the low-low vacuum pressure (12" Hg) causing both vacuum pumps to simultaneously turn on to charge the tank back up to normal system pressure (18" Hg).

2. Single Vacuum Pump - This event corresponds to the operation of one vacuum pump during the standard vacuum charging of the system between the cut-on pressure (14" Hg) and the cut-off pressure (18" Hg).
3. Discharge Pump- This event corresponds to the operation of the discharge pump as it pumps down and transfers the contents of the VCT to the larger holding tank [21].

The signatures generated by each pump are easily discerned from each other due to their relative size and shape. For instance, the starting transient of a vacuum pump occurs over a different time scale than the starting transient of the discharge pump. The discharge pumps also have a lower overall steady state magnitude and usually run much longer than the vacuum pumps. The NILM can accurately record the full system schedule in real time. Real power consumption over a typical hour of operation of the system can be seen in Figure 2-5 below:

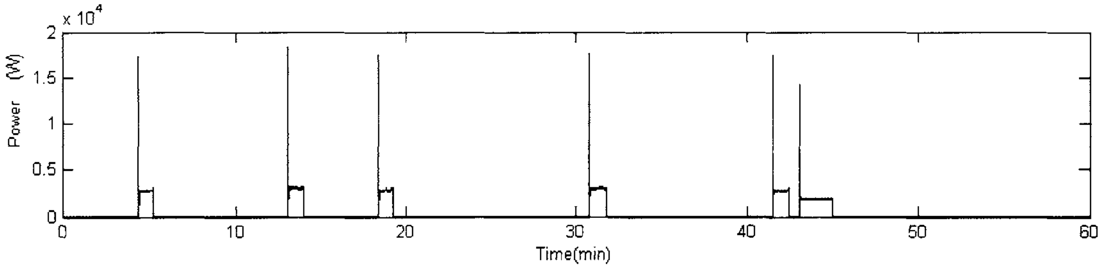


Figure 2-5- Typical Hour of CHT System Operation onboard the *USCGC Seneca*. This plot depicts five nearly identical vacuum pumps runs and one transfer pump run at approximately minute 44.

2.1.2 Current Monitoring Practice Shortcomings

The Main Propulsion Control and Monitoring System (MCPMS) onboard the 270' Famous class is not intended to monitor the operation of the CHT system. MCPMS only recognizes two general critical fault conditions sent via the local control panel: a high tank level alarm state that occurs at 80% capacity of the collection tank and vacuum pump overloads that occur after excessive operation. During both alarm conditions the local control panel sounds a siren and the system locks out automatic operation until a manual reset has take place. MCPMS only receives a signal of indicating this shut down had occurred. Because this automated monitoring system does not provide adequate monitoring capabilities, other system checks are logged hourly by watch standers that record the following parameters in order to obtain an indication of system abnormality:

1. Vacuum Pressure – The watch stander checks local gauge to see if the vacuum pressure in the tank is between the set ranges of 14 to 18" Hg.
2. Seal Water Tank Temperature- The temperature of the seal water is read and recorded off of a local temperature gauge mounted on the seal water tank by the watch stander. The temperature of the water used to prime and cool the vacuum pumps should not be in excess of 100 degrees Fahrenheit. A higher temperature may indicate excessive vacuum pump operation.

3. Seal Water Tank Sight Glass – The sight glass mounted on the side of the seal water tank should be clear to ensure no sewage had been sucked up by the vacuum pumps and deposited in the seal water tank.
4. VCT Viewing Port- This clear 4"viewing portal on the top of the tank is used to see inside the tank to check overall sewage level inside the VCT

The above checks provide general indications of abnormal operation without directly pinpointing a certain problem. There are several factors that often prove this type of monitoring to be fraught with shortcomings that negatively impact the serviceable life of the system:

1. Leaks- Leaks in the system at toilets or fouled check valves can cause excess running that does not cause overloads or excessive seal water tank temperature. Frequency of runs increases dramatically and intermittent watch stander oversight cannot correctly detect the presence of these leaks on cycling systems.
2. Clogged Gauge Lines- 1/2"gauge lines to the pressure gauges can become clogged with waste. This prevents proper system pressure from being read and slows down actuation of the pressure gauges and switches. This is a fairly common occurrence and is unavoidable due to the nature of the system.
3. Viewing Port- The 4" window into the tank becomes dirty and occluded resulting in the inability to view internal levels of sewage inside the VCT.
4. Seal Water Tank Temperature- This temperature is affected by the ambient temperature inside the Auxiliary Machine Space which can vary greatly depending on the seasons and the location of the ship's operation.
5. Increasing Age of the System- Due to the necessity of the system to shipboard operation and habitability, temporary fixes and settings are often used to bypass faulty alarm conditions. These can result in slow degradation of the system. Multiple crewing and transfer of personnel could result in these settings being left for the next crew.
6. Physical Layout- Discharge pumps and vacuum pumps are located on different decks making the timing of operations hard to observe by one watch stander or troubleshooter.
7. Fouled or Broken Level Indicating Probes- These probes can become coated with waste causing improper transfer pumps operation. This can cause the level to rise to a point where gauge lines become clogged and waste is sucked up by the vacuum pumps.
8. Troubleshooting- The task of finding and fixing problems is very unpleasant and usually very time consuming. This fact usually postpones corrective action if the system is still operating marginally well.

Because of these factors, casualties can remain in place for a long time without being detected or corrected. It is during this period that excessive pump wear occurs.

2.2 NILM Detection of System Clogs

One problem often observed by ship's force is the slow clogging of gauge lines and orifices. This casualty can severely limit ships force's ability to detect and diagnose problems.

2.2.1 Pressure Gauge Line Clogs

One of the most common complaints about many shipboard sewage systems is the inability to keep the smaller gauge lines clear of waste build up. As waste slowly builds up over time, the local vacuum gauges become more and more unreliable until the crew no longer trusts their readings. Often there will be three or more gauges to measure the vacuum level in different branches of the system. Over time all but one gauge will be neglected due to the frequency and difficulty of clearing these lines. These gauges are not considered "mission critical" so this preventative maintenance is often pushed farther and farther down the work list onboard aging ships.

Reading the local gauge is a very important part of finding leaks onboard ships. The slow drop of the needle indicates a leak while a quick drop in pressure indicates a flush or system usage (see Figure 2-25). As the gauge line clogs this needle becomes sluggish and the gauge reading itself becomes less and less accurate. When the line is severely clogged the needle may only cycle between 1" Hg during each charge and discharge. This inaccuracy can hinder troubleshooting efforts by eliminating one of the most effective tools in determining system health. In other instances this inaccuracy can lead to human errors in operation. Examples will be detailed in the following section.

2.2.2 Pressure Switch Line Clogs

2.2.2.1 Pressure Switch Description

The vacuum pumps are controlled by two pressure switches mounted onto the side of the VCT. One switch controls the normal operation of the vacuum pumps by cutting on a single lead pump when the vacuum reaches 14" Hg and cutting off the same pump when system vacuum pressure reaches 18" Hg. The second vacuum switch operates the backup vacuum pump and is set to cut in at 12" Hg to aid the leading pump under unusual instances of heavy loads. Upon reaching 18" Hg both pumps de-energize in unison. Both switches can be manually adjusted by altering the range and differential settings using dials inside the switch. The differential adjustments adjust the vacuum difference between the cut-in and cut-out points. The range adjustment raises or lowers the cut-in points [21].

Both switches share the same gauge line and operate in much the same way as a pressure gauge. Unfortunately these switches have no visual readout to determine what system pressure is being read. Figure 2-6 shows a picture of the switches and the layout of the switch internals.

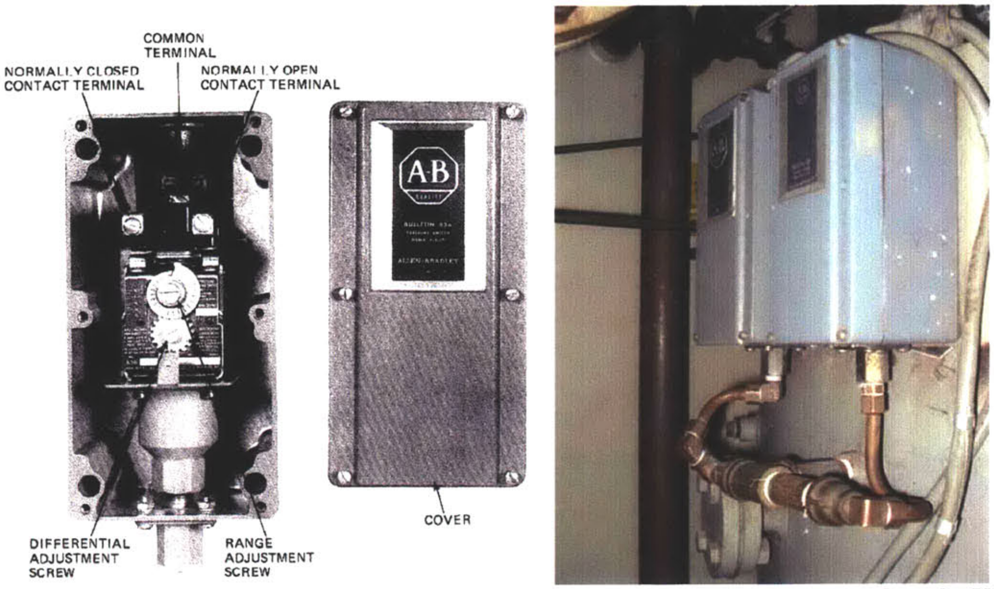


Figure 2-6: Pressure switch internals [21] (left) with picture of both switches mounted on the VCT sharing the same gauge line (right).

2.2.2.2 *Poor Switch Maintenance Caused by Gauge Misinformation*

Onboard the 270' Famous class cutters the Electricians Mates (EM's) are responsible for the maintenance of the pressure switches and controller that operates the CHT system. Depending on the specific platform either the Damage Controlmen (DC's) or the Auxiliary Division Machinery Technicians (MK's) are responsible for the proper operation of all mechanical components such as the VCT, pumps, vacuum seal, check valves, gauges and gauge lines, etc. This sharing of responsibility paired with clogged gauge lines caused a man-made casualty that caused excessive wear on the vacuum pumps for a number of days.

As part of a regular maintenance procedure, the electricians checked to see if the vacuum pumps were properly cycling system pressure between 14"Hg and 18" Hg according to specification. Initial investigation of the local gauge indicated the pumps were cycling in between 11-12" Hg in the system. Not knowing the gauge line was clogged and the pressure gauge was inaccurate, the EM's reset the pressure switch range and differential settings until the local gauge cycled between 14 and 18" Hg as per the manual. Once this maintenance task was completed the Electrician's Mates put the system back online not knowing the resulting pressure switch settings were far outside the vacuum pump's normal operating range.

Over the next week the seal water tank temperature rose and the pumps became to become warm enough to cause overload alarms. The Auxiliary Division investigated the problem assuming there was a leak in the system but could not find one large enough to cause the symptoms that the system was exhibiting. After some time the gauge lines were removed from the tank and were found to be packed solid with waste. The ½" line feeding the pressure switches was packed solid as well. A picture before and after cleaning the orifice leading to the gauge line can be seen in Figure 2-7.

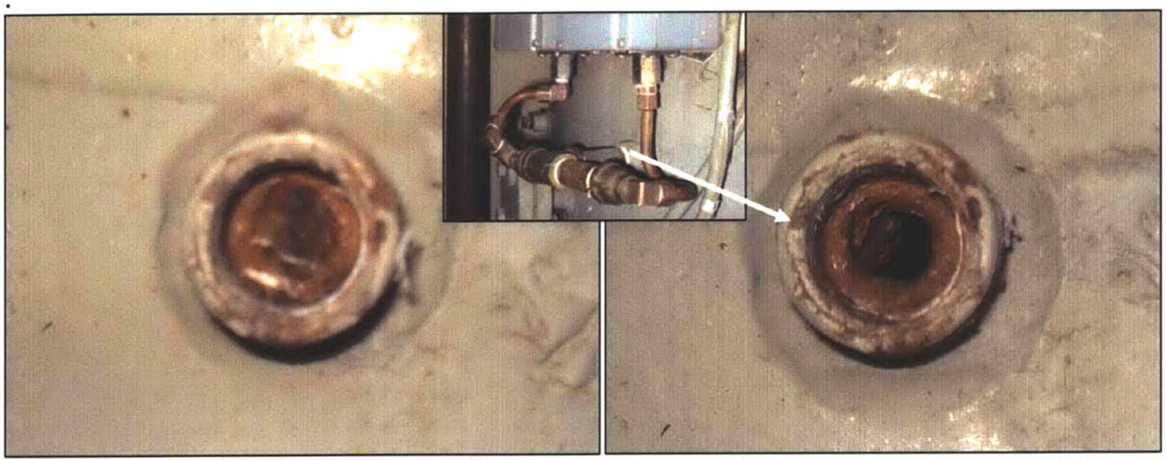


Figure 2-7: Clogged pressure switch gauge line VCT orifice before (left) and after (right) cleaning in response to a casualty.

After the cleaning and restoration of the gauge lines the system was placed online. The now properly functioning vacuum gauge indicated the pressure switch had been improperly set, forcing the vacuum pumps to cycle between 21 and 23.5" Hg. This is clearly at the far edge of the intended operating capacity of the pump as indicated from vacuum pump curves from the CHT system manual (Figure 2-8). This figure shows the capacity of the pump (in cfm) drop off sharply as the vacuum approaches 24" Hg. At this edge of the operating profile, the pump would run for much longer periods of time trying to achieve a very high system vacuum.

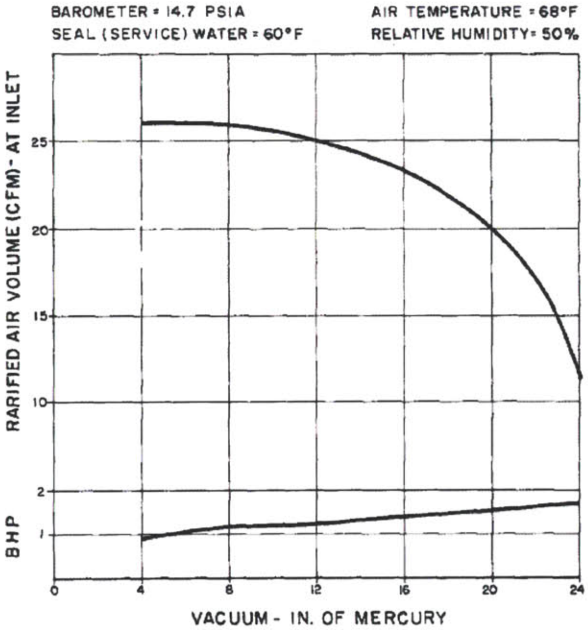
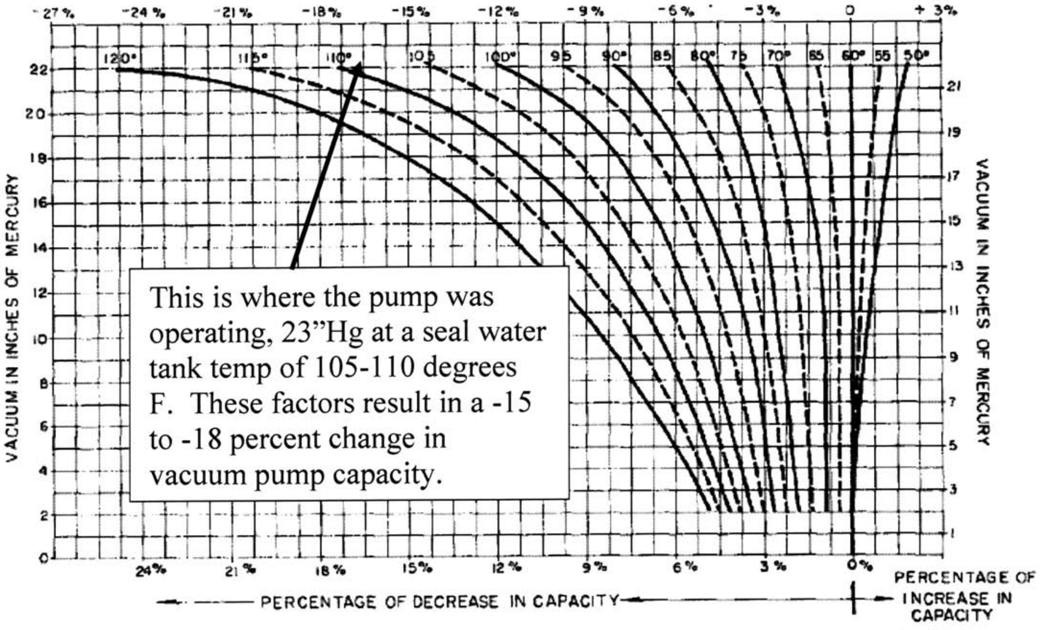


Figure 2-8: Vacuum pump curve [20]

Excess vacuum pump runs would also cause the seal water tank to increase in temperature. This increase in temperature would result in a 15-20 percent decrease in capacity as the seal tank water temperature approached 105 degrees Fahrenheit. This increased seal water temperature causes the pumps to be even less effective causing the pumps to run for even longer periods of time. This appropriate correction curve can be found using Figure 2-9.



This is where the pump was operating, 23"Hg at a seal water tank temp of 105-110 degrees F. These factors result in a -15 to -18 percent change in vacuum pump capacity.

Figure 2-9: Effect of service water temperature on liquid ring vacuum pump capacity [21]

The technical publication for the vacuum pump states "each pump is provided with a vacuum relief valve set at 22" Hg to prevent the pump from operating at an excessive vacuum" [21]. Unfortunately these relief valves had been removed from the entire fleet years ago due to troublesome maintenance concerns according to senior shipboard enlisted personnel. Due to the incorrect settings and in agreement with the performance curves, the pumps began to run for extremely long periods of time to achieve a vacuum of 23.5" Hg. A normal three hour plot is compared to the incorrectly set pressure switch condition in Figure 2-10 below:

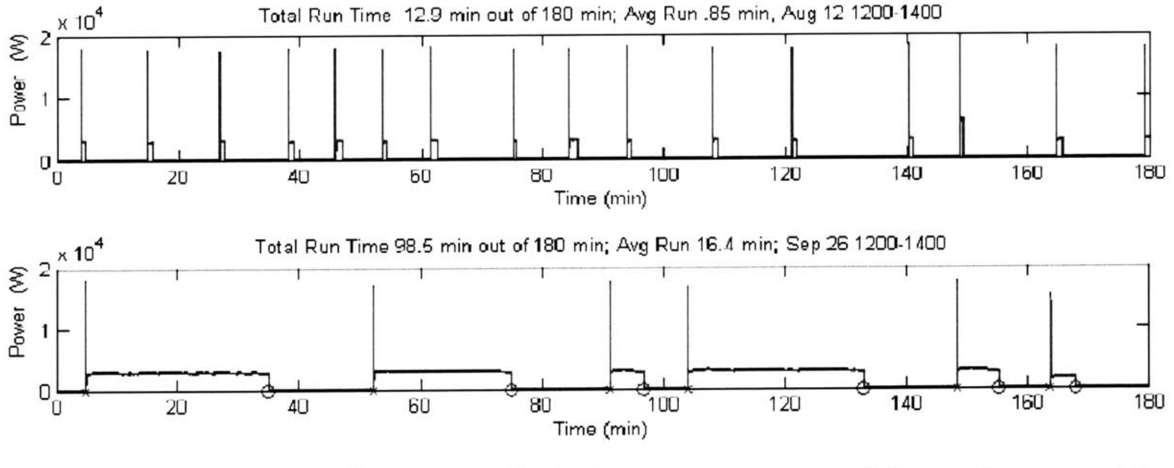


Figure 2-10: Normal three-hour power plot (top) ; *Seneca* pressure switch casualty power plot (bottom).

This excessive errant pressure switch setting caused the vacuum pumps to run for excessive amounts of time while trying to achieve an extremely high system pressure. Upon reviewing NILM documentation it was found that this problem persisted from 1800 Sep 25th 2006 and lasted until 1400 Oct 3rd 2006. This casualty resulted in approximately 34 days of wear assuming the conservative estimate that the pumps ran approximately 30 minutes every hour during this eight day casualty period.

This casualty is a fine example of the problems that can occur from human error induced by clogged gauge lines. This human error, however, could have easily been caught with the aid of a visual power schedule that the NILM can provide.

2.2.2.3 <u>Prediction of Gauge Line Clogging</u>

The only indication of gauge-line clogging is limited to the visual observation of the sluggish or limited actuation of the pressure gauge needle. Unfortunately there is no clear way to differentiate between whether or not the gauge is incorrect or if the pressure switches themselves are out of calibration. The only way to find out for sure is to remove all gauge lines and inspect them for blockage. This practice is unpleasant and time consuming and is not performed unless there is a certain casualty present.

In an attempt to find a non-intrusive method of predicting ½" gauge line blockage, it was observed that the pressure switch operates under much the same principle as a vacuum pressure gauge. The lines are identical in size and connect to the VCT in similar locations. According to this logic, it is assumed the pressure switches would become inaccurate in much the same way the needles on the pressure gauges. To test this hypothesis the average vacuum pump run time per system charge was calculated for the two months prior to the pressure switch casualty described in Section 2.2.2.2. The results can be seen below in Figure 2-11.

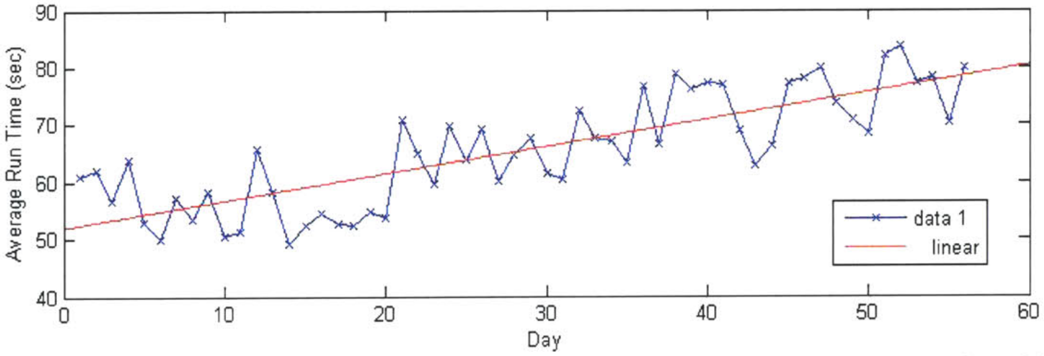


Figure 2-11: Trend in the average run-time of the vacuum pumps in the CHT system aboard the *Seneca*. The trend line is included to demonstrate that an upward trend was in place for nearly two months prior to the discovery of the clogged switch and gauge lines.

It is clear from the plot that the run time trend increases significantly over the two months prior to the known gauge line clog casualty. The average run time for a single pump to charge the system increased from approximately 52 seconds to 80 seconds. As the pressure switch line becomes more and more blocked the pressure switch control of the vacuum pumps becomes more and more inaccurate. After restoring the CHT system to correctly cycle between 14 and 18" Hg using a single vacuum pump, the average time per charge was recorded to be approximately 60 seconds. With the reasonable assumption the performance of the vacuum pumps did not change during this period, this increase in runtime is responsible for an approximate 30% increase in wear and power usage per charge according to this analysis.

Although this operating profile change is more gradual in nature, a prediction of gauge or pressure switch line blockage can be approximated by observing the average increase in run time per single vacuum pump charge of the system. After this parameter is properly set and recorded, any deviation noted over time can be treated as a possible indication of gradual clogging that impairs system performance while increasing unnecessary wear. This non-intrusive method can be accomplished quickly and easily by a NILM equipped with appropriate diagnostic software.

2.2.3 Vacuum Pump Priming Orifice Clog Detection

Both vacuum pumps are mounted on a 100-gallon capacity seal water tank with interconnecting piping and valves. The seal water tank provides the water necessary for the pumps operation. The seal water is circulated by the vacuum pumps during operation providing a cooling effect and a liquid seal ring for the pumps [21]. Upon start up, seal water is automatically sucked into the pump housing through a small line connected to an orifice on the pump body. If this line or orifice becomes clogged the pump cannot prime and little or no vacuum is drawn. Without doing any work the power drawn by the pump decreases significantly. A plot of this casualty can be seen below in Figure 2-12

.

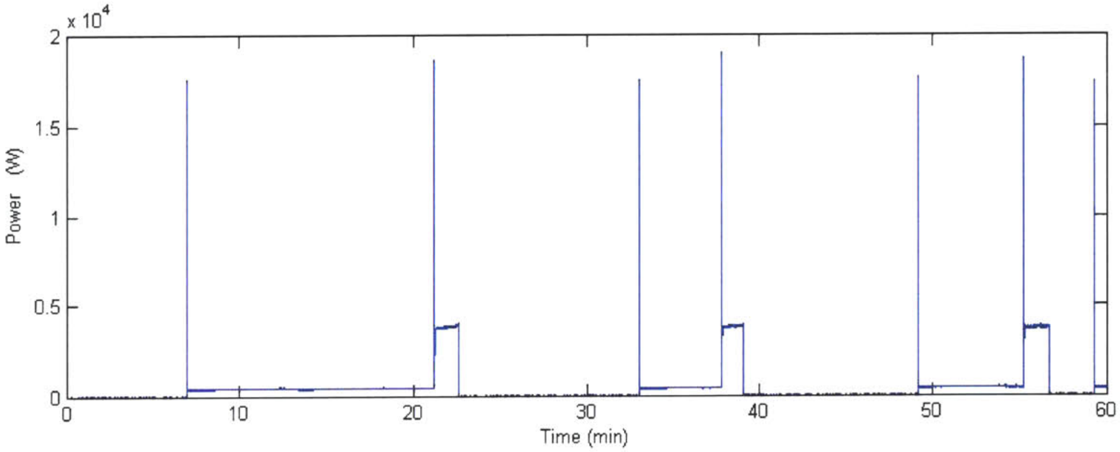


Figure 2-12: Power plot of the *Seneca*'s CHT system with one vacuum pump unable to achieve vacuum due to a clogged seal water orifice.

Figure 2-12 shows the vacuum pump that is unable to prime starting first each time. Unable to draw a significant vacuum, the faulty pump runs until the low-low vacuum pressure of 12" Hg is reached and the properly functioning backup pump is kicked in by the secondary pressure switch. With one properly functioning pump now online, the system is drawn down to 18" Hg and both pumps simultaneously shut off. The relay responsible for alternating the pumps leads with the faulty pump and is reset each time due to the start of the correctly functioning back up pump.

This pump housing orifice clog occurs due to the introduction of sewage into the seal water tank via the vacuum pump air intake. This can occur when the sewage level inside the VCT reaches a high enough level for the sewage itself to be sucked up into the vacuum pumps. Although the level indicating probes inside the VCT are meant to shut the system down before this could ever occur, a fouled probe or probe casualty could cause this to happen. With a mixture of sewage and seal water constantly cycling through the vacuum pumps during operation, blockages can be a result quite quickly after introduction of sewage into the seal water tank. Pictures from a repair prompted by NILM data analysis alone can be seen below in Figure 2-13:

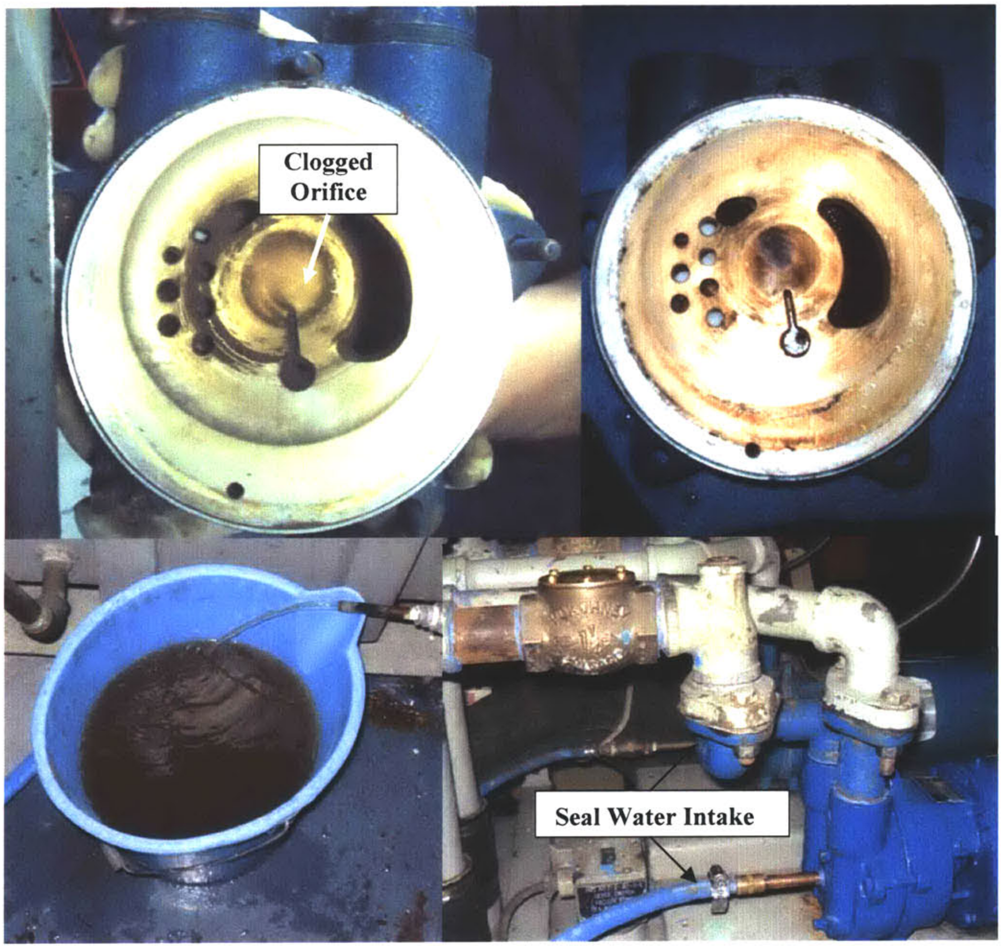


Figure 2-13: Pictures from the loss of prime casualty repair onboard the *Seneca*. Pump housing prior to cleaning (above left) and after cleaning (above right). Sewage contaminated seal water (bottom left). Photograph showing intact pump with seal water line entering body of pump housing (bottom right).

This casualty occurred on two separate occasions onboard the *Seneca.* In both cases the casualty had existed for extended periods of time with no knowledge of the casualty. The first orifice clog casualty started on October 5th 2006 and persisted until December 28th 2006 without knowledge of the loss of prime by the crew. The second casualty began on

Feb 22nd 2007 and lasted until NILM data analysis prompted a repair on March 29th 2007. During the entire 175 day time period spanning both casualties, 119 days of improper operation had occurred due to a loss of prime. With the faulty pump running in excess of twenty minutes at a time, it is clear that the current monitoring methods are lacking. Had the power data been visible to the crew, both casualties could have been found within an hour of the initial clog. Future NILM software could have detected this change by noting a lower than average steady state power after the initial start up.

2.3 NILM CHT Controller Diagnostics

The NILM provides a unique tool that can monitor and record the power signal from all four pumps in the system. Controller or probe casualties will result in erratic behavior by the discharge pumps that cannot be easily detected by current monitoring methods. The discharge pumps are also located one deck below the control panel in the lower level of the Auxiliary Machine Space making it harder to observe the pump's erratic behavior.

2.3.1 Fouled and Damaged Level Indicating Probe

The sewage level indication and discharge pump control is monitored by a set of four vertical conductivity probes. A technical publication diagram and picture can be seen in Figure 2-14 [21] :

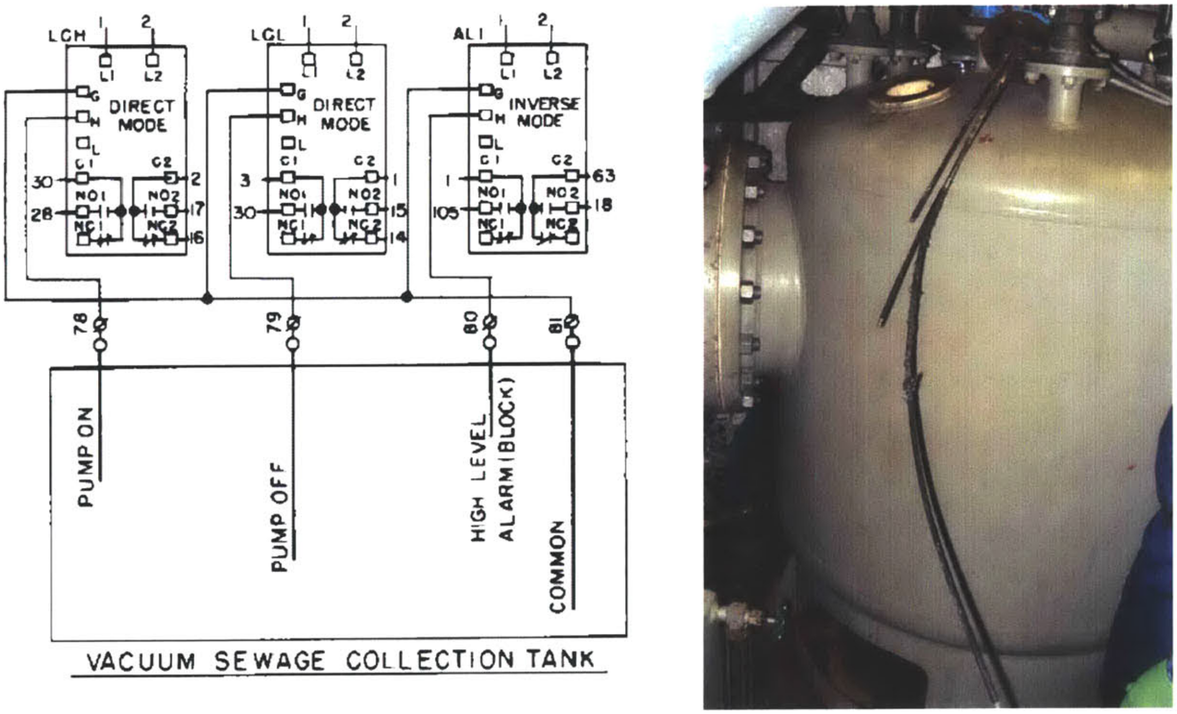


Figure 2-14: Picture/Electrical Schematic of Level Indicating Probes [21]

These probes consist of a set of insulated metal probes that use the contents of the tank as the medium to complete the control circuit. Only the tips of each probe are exposed to the sewage. The circuit is completed when the tips of the probes make contact with the liquid contents allowing the electrical the signal to the common ground. The control circuits are broken when the sewage level clears the probes during a discharge pump run. The discharge pump cycles the sewage level inside the tank between the 33% and 5% full levels. The typical discharge pump run lasts about 3 to 4 minutes as 120 gallons of sewage is transferred to a larger holding tank. These probes control the following functions at the following levels [21]:

1. Full tank blocking alarm at the 288 gallon level (80% full). Automatic vacuum pump operation is blocked to prevent sewage from entering vacuum pump housing.
2. Lead discharge pump start and 1/3 level indication at the 120 gallon mark (30% full).
3. Discharge pump stop and common probe at the 18 gallon level (5% full).
4. Sewage level rising/falling condition between the pump star and stop probe.

The tips of these probes often become fouled by the contents of the tank over time causing improper discharge pump operation. This could lead to VCT sewage levels rising high enough to be sucked into the vacuum pump housing, excess running of the discharge pumps, and/or frequent intermittent operation. A picture of a fouled probe before and after a cleaning can be seen in Figure 2-15.

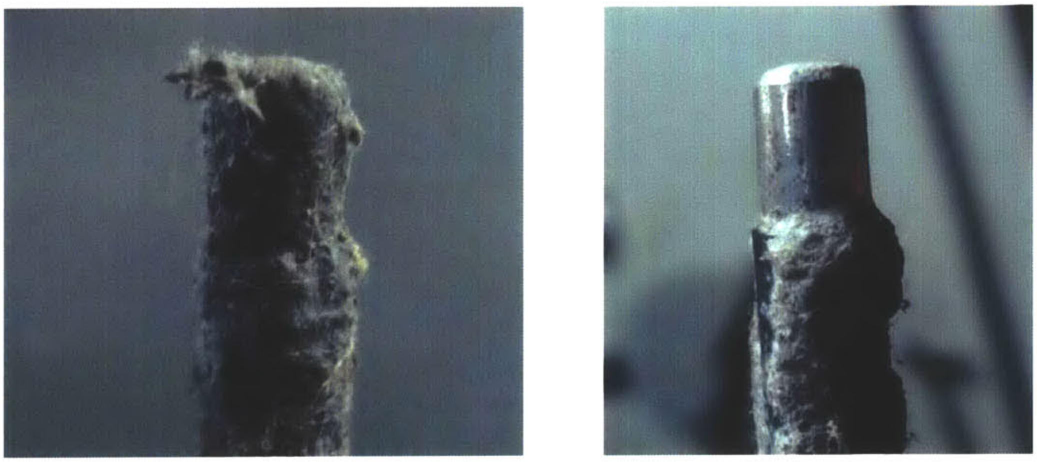


Figure 2-15: *Escanaba's* fouled probe tip before (left) and after (right) cleaning

In certain cases probes have become loose or damaged over time causing erratic pump operation. In addition to the diagnosis of the Feb22-Mar29 2007 loss of prime casualty onboard the *Seneca*, NILM data analysis also uncovered erratic discharge pump operation beginning to occur at 1800 on March 23rd 2007. This can be seen in Figure 2-16.

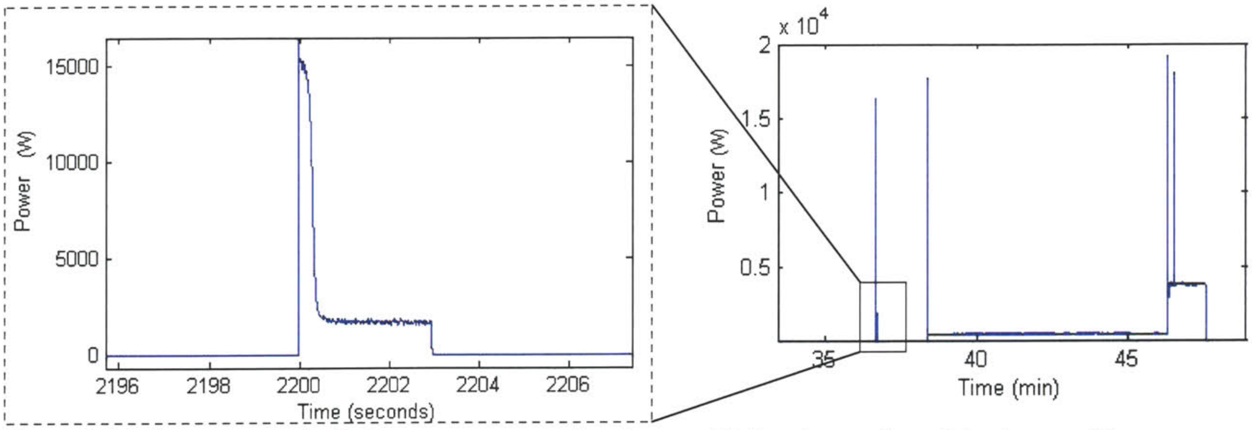


Figure 2-16: ***Seneca's*** **erratic discharge pump operation began with the observation of short runs of 3 seconds or less. The short run appears to be a power spike on the hourly plots. When observed closely the magnitude of the steady state period clearly defines it as a transfer pump.**

After some time the erratic shorter runs of the discharge pump began to be accompanied by much longer discharge pump runs. Figure 2-17 shows a 16 minute discharge pump run occurring the day before the seal water clog was cleared. This is much longer than the 3-4 minute average discharge.

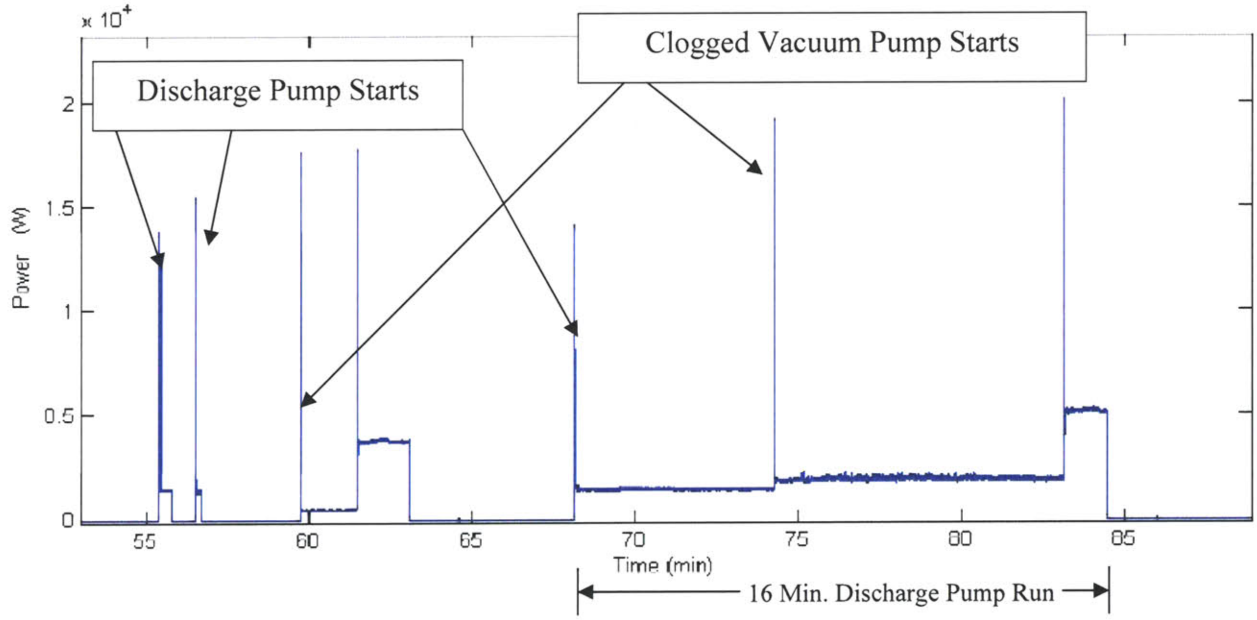


Figure 2-17: Longer transfer pump control malfunction due to damaged probes paired with loss of prime vacuum pump casualty.

Knowing erratic transfer pump operation was due to a fouled of faulty probe, ship's force removed the dirty (and no longer transparent) viewing port to find the common probe lying at the bottom of the VCT. Pictures of this casualty can be found in Figure 2-18.

Figure 2-18: From left to right- Broken common probe lying in the bottom of the VCT; Probe flange with no probe attached; Unscrewed probe tip showing heat wrap had failed allowing the probe to unscrew; Entire probe after being pulled from the bottom of the VCT.

In this case the detection of the common probe lying at the bottom of the VCT could have been greatly facilitated had the viewing port not been completely covered in sewage. A picture of the viewing port prior to cleaning can be seen in Figure 2-19.

Figure 2-19: Dirty VCT viewing port.

Many other instances of erratic discharge pump operation have been recorded with the NILM. Unfortunately the cause of and repair of those casualties were not as well documented. In all cases, visual NILM observation would have quickly made it apparent to watch standers that something was not correct. Figures 2-20 and 2-21 document two possible instances where fouling or probe issues were may have been the cause of the errant behavior of the discharge pumps.

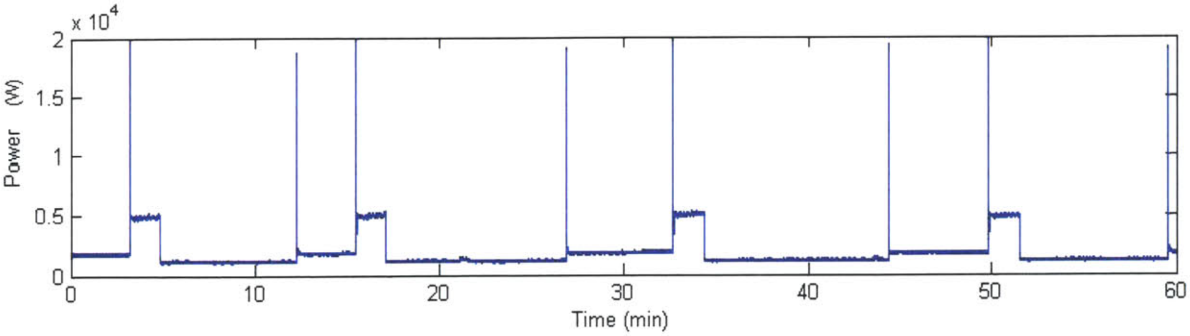


Figure 2-20: This plot shows the discharge pump running for the entire hour while the vacuum pumps cycle with a loss of prime casualty due to a seal water orifice blockage.

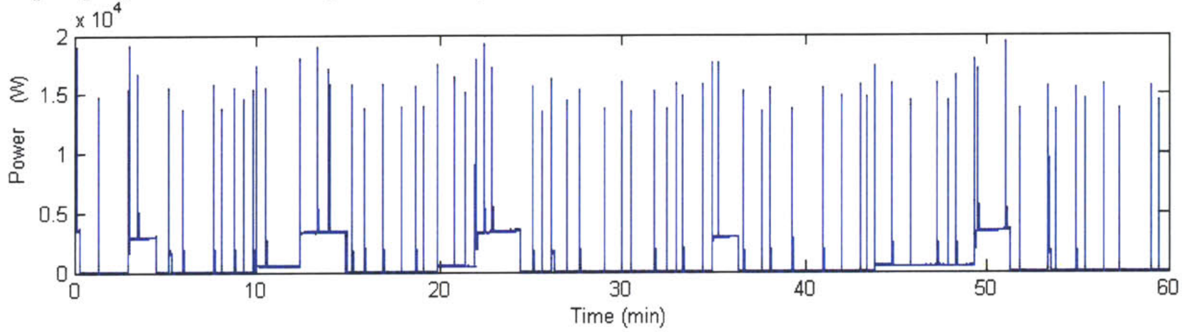


Figure 2-21: This plot documents a loss of prime casualty accompanied by a very large number of very short discharge pump runs.

In these cases the NILM could have detected both the abnormally short runs in Figure 2-21 and the abnormally long run in Figure 2-20 by calculating the step increase in power drawn by each event and the duration of time that that increase occurred. During normal operation the longest run should only occur for 3-4 minutes as the discharge pumps run. The shortest run should last close to 30 seconds in the case of a double vacuum pump start. Anything outside these parameters would result in a flag to go up by the NILM indicating that abnormal operation had occurred.

2.3.2 Controller Casualties Due To Aging System

The Famous Class Cutters under observation for this thesis were commissioned between 1983 and 1991 making most of the newest class of Coast Guard Cutters almost twenty years old [22]. The CHT system onboard the 270' Famous Class cutters is one example of an aging system performing a dirty job in an unforgiving environment. The Auxiliary Machine Space temperatures can approach 90-95 degrees Fahrenheit during southern summer patrols in the Caribbean. All of these factors lead to the wearing down of important electrical components responsible for the control of the system. With replacement parts sometimes often not readily available, short term fixes meant to keep the ship and its crew operational sometimes become forgotten or not passed down from crew to crew.

2.3.2.1 *Escanaba's Probe and Controller Casualty*

The *Escanaba's* CHT system was certainly an example of an aging system that had gathered an assortment of temporary fixes over the years. Installation of the NILM onboard the *Escanaba* revealed the power plot shown in Figure 2-22. This power plot was recorded directly after a full chemical cleaning of the system that had caused several minor leaks to occur. These leaks caused the vacuum pumps to charge the system 13 times in the hour at a fairly regular interval. The errant spikes marked by the arrows in Figure 2-22 were found to be transfer pump starts of two seconds or less. These errant spikes lead the crew to initially suspect a fouled or faulty probe.

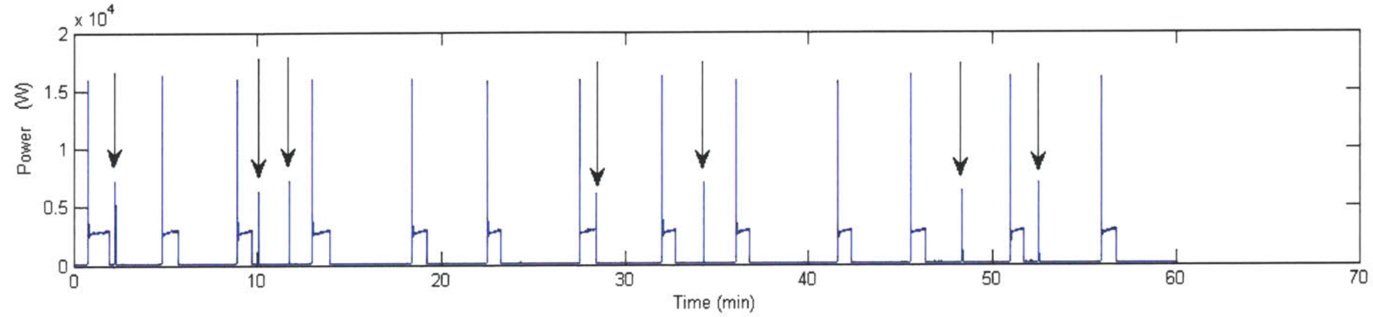


Figure 2-22: Initial power plot after installation onboard the *Escanaba*. Errant spikes marke arrows indicated a short transfer pump start.

Opening the tank and removing the probes revealed the probes were in poor condition. The insulation on the longest probe responsible for controlling the transfer pump shut off at the low level mark was flaking and compromised in several locations. It was also heavily coated in waste. Repairs of the coating had been attempted in the past using insulating heat wrap that had corroded and slipped down to the tip of the probe where it hung off, blocking the normal control signal transmission. Due to the lack of a replacement probe, the probes were cleaned as well as possible and the more insulating wrap was placed on the probe to keep the CHT system in operation while waiting for a replacement part. A picture of the damaged probe can be found in Figure 2-23.

Figure 2-23: Corroded probe coating next to newer probe coating (left); Previous repair insulation blocking control signal while hanging off the tip of the probe (right).

Hoping this had solved the problem the system was placed back online. Over the following days the NILM was used to check the operating schedule of the pump to determine if the temporary correction had indeed fixed the problem. Unfortunately for the *Escanaba* the discharge pump problems continued indicating that there were larger problems with the circuitry of the panel itself. An investigation of the control panel revealed a system of electrical jumpers that should not have been there. This clearly was evidence of a temporary fix that had been forgotten as personnel transferred on and off the ship.

To further trouble shoot the system, the VCT was filled manually via fire hose to observe the signals sent to the control relays responsible for operating the discharge pump. This investigation revealed that the control panel had been wired so that the discharge pump would energize when the sewage level reached the bottom probe (5% capacity) instead of the middle probe (33% capacity) level. The discharge pump would then correctly secure upon clearing the longest probe. This incorrect wiring in effect served to turn the discharge pumps on and off after only having pumped approximately 2 inches worth of sewage each cycle. This explained the frequent short operation of the discharge pumps.

Further investigation revealed a burnt-out bulb and wiring that resulted in the appearance of normal operation according to the level indicating lights on the front of the control panel. This casualty had been occurring for an indefinite amount of time not less than two years. Without clear viewing panel, properly functioning indicating lights, or a reason to investigate the system in depth the crew of the *Escanaba* had no reason to believe they had any problems with the transfer pumps. NILM power data analysis alone had indicated otherwise.

2.3.2.2 Seneca Vacuum Pump Relay Casualty

The final example of a casualty diagnosed by the NILM occurred onboard the *Seneca* when the relay controlling the operation of the vacuum pumps began to act abnormally. The power plot for a single errant pump run can be seen below in Figure 2-24:

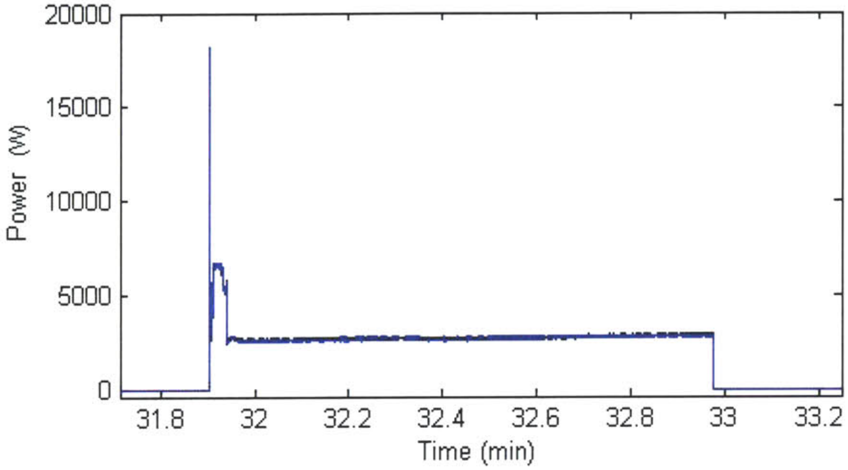


Figure 2-24: Errant vacuum pump run caused by faulty relay onboard the *Seneca*. Both vacuum pumps cut on simultaneously with one cutting off after only a few seconds.

The plot shows that both vacuum pumps energize simultaneously. This should only occur when the pressure suddenly drops to 12" Hg as described before. After only a few seconds one pump shuts down while the other one continues to charge the system for a normal length of around one minute. This behavior went unnoticed onboard the *Seneca* for an extended period of time until finally detected and corrected during a fouled probe casualty.

2.4 NILM CHT Leak Detection

2.4.1 Basic Vacuum Leak Information

The CHT system relies on a vacuum created by the vacuum pumps. When leaks occur, there can be either a very slight or very dramatic increase in the frequency of vacuum pump runs depending on the size of the leak. Each toilet flush or any other system usage event causes a step decrease in system vacuum pressure. Any leak will create a gradual decrease in system pressure. Figure 2-25 plots the simultaneous recording of both VCT internal vacuum pressure (top) and power usage as recorded by the NILM (bottom) over a twenty two minute period. This plot had been previously generated by LT Mosman [20].

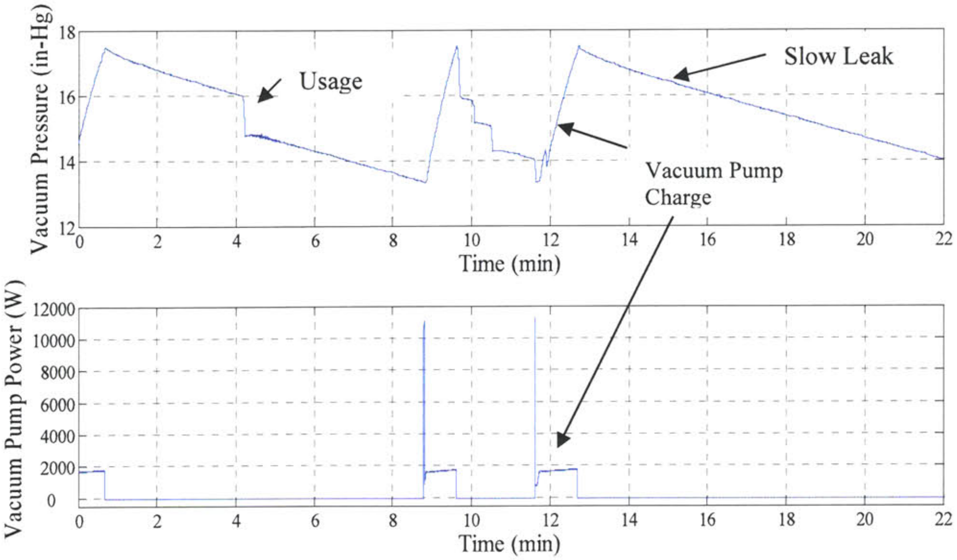


Figure 2-25: *Seneca* sewage system pressure trace (upper plot) and vacuum pump power (lower plot) chronologically aligned. The pressure decreases are caused by a system leak (the gradual decrease) and by toilet flushes (the step decreases). [20]

As the leak becomes more extreme, the slope of the gradual pressure drop becomes more extreme, causing more frequent pump cycling. Leaks can occur at numerous usage locations throughout out the ship or in the AMS space due to mechanical pump or check valve failures. Current leak detection is limited to the observation of a rise in seal water tank temperature or the observation of an audible hiss from a fixture. This audible hiss is easily drowned out by other machinery in the Auxiliary Machine Space or other shipboard noise in the bathroom facilities. A very large leak would cause the frequency of pump runs to increase to the point of overload which results in an audible alarm and shut down requiring a reset. One such leak or combination of smaller leaks is often needed to prompt ship's force to detect and begin troubleshooting a significant leak. Small leaks can go undetected for very long periods of time.

2.4.2 Previous Leak Detection Research

LT Mosman's prior research and leak diagnostics assumes that the CHT system was working properly and that no other system casualties were present. The times between vacuum pumps runs was recorded and histograms were plotted to show the distribution of these time periods. Identification of a leak could be made by noting a change in the shape or location of the histogram peak. Experimental data collected onboard the *Seneca* was used to verify the validity of the modeling of the system and a thorough diagnostic process was set up to detect leaks during normal operation. A thorough description of this process can be found in his thesis [20].

This thesis builds on prior research by focusing on the abnormal behavior associated with system casualties. The resulting diagnostic approach will result in a two tier approach of constantly monitoring the CHT system for smaller leaks while immediately notifying the crew of any abnormal behavior or system casualties.

2.4.3 Escanaba: Detection of Major Vacuum Leak

LT Mosman [20] used statistical analysis to differentiate periods of high usage and the presence of leaks. In a much more basic role, the plotted power schedule of the NILM can provide invaluable visual input in regards to the frequency of operation of the system as compared to a normal schedule. Figure 2-26 compares a normal hours worth of operation to a large leak at the check valve that had been misdiagnosed and undetected onboard the *Escanaba* for several months.

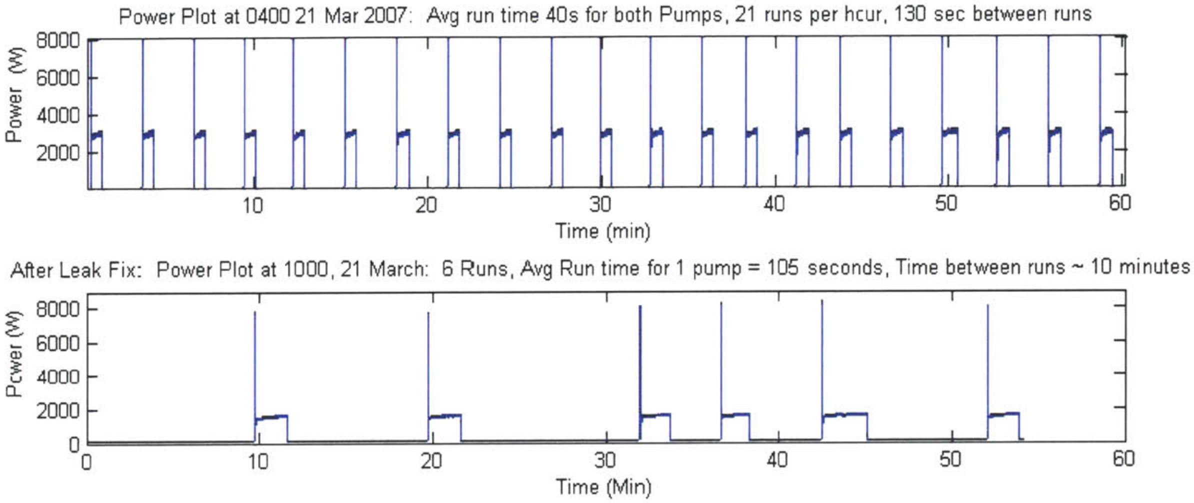


Figure 2-26: Power plot an hour before (top) and an hour following (bottom) the detection and repair of large check valve leak onboard the *Escanaba*.

The aging check valve responsible for the leak consists of rubber flapper that could not seat when the bronze-rubber seal face became dirty and pitted enough to be unable to create an airtight seal under vacuum while the pumps were not in operation. A picture of the check valve and the flapper after it had been cleaned can be seen in Figure 2-27. This fault state had previously been successfully detected by the NILM during LT Mosman's research onboard the *Seneca*. This separate occurrence of the same problem onboard the *Escanaba* supports the fact that this is a class-wide problem that could be easily identified immediately upon failure of the vacuum seal. In both cases the crew had no awareness of the leak until NILM researchers had pointed it out to them.

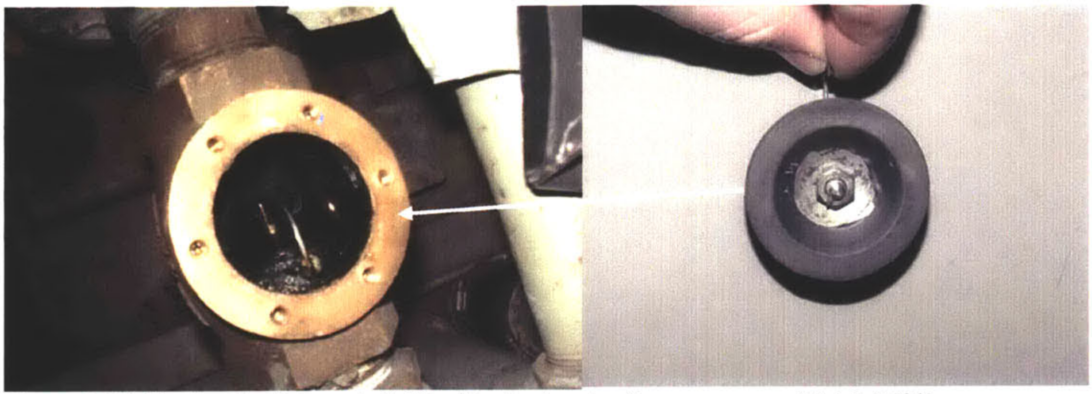


Figure 2-27 Check valve internals (left) with check valve flapper removed (right) [20]

The sequence of events leading up to the check valve vacuum casualty onboard *Escanaba* had greatly impaired trouble shooting efforts and had confused the crew as to the reason why the pumps were overloading. During the month prior to the leak a faulty overload sensor caused several seemingly unnecessary overload alarms. Frustrated with failed attempts at troubleshooting this minor electrical problem, ship's force set the vacuum pumps to energize in unison to work together to charge the system. This prevented the overload alarm from repeatedly sounding while waiting for replacement parts. The large check valve leak began while ship's force was waiting for the replacement sensor. Upon replacement of the sensor the overload problem continued to persist due to the increased cycling induced by the leak and not because of the faulty sensor. This prompted the crew to place the entire pump and motor under suspicion with intent to replace them both. Prior to this expensive measure the check valve leak was found by the NILM and isolated for repairs. The system was returned back to normal operation using single vacuum pump to charge the system. Figure 2-28 shows the four hour period the check valve was found and corrected. A drastic change can be observed.

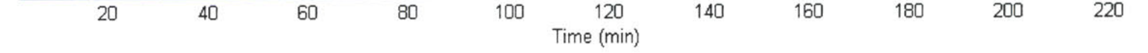


Figure 2-28: Plot of power during correction of leak fix onboard the *Escanaba*.

In this rather extreme case, the chain of events had lead to an extreme amount of unneeded usage and wear on both vacuum pumps. Analysis of the data from their last operational patrol reveals that the leak started on January 10th 2007 until the leak was corrected on March 21st 2007. During that time period both pumps operated on average of roughly 20 times per hour for the duration of a minute. This seventy day period resulted in over a years worth of unnecessary wear on the pumps and motors.

If the crew been able to observe the real time power plots the leak could have been quickly diagnosed and found within minutes of the seal failure. This type of visual information paired more sophisticated diagnostic software currently under development could provide useful and telling information could be used to accurately diagnose both small and large vacuum leak casualties.

2.5 CHT System NILM Diagnostics Conclusion

From the observation of both the *Escanaba* and the *Seneca* it is clear that the current methods of monitoring the CHT system fail to detect minor casualties that do not cause overloads or alarms. These minor casualties, however, contribute to excessive wear that eventually leads to shortened lifespan of equipment while wasting energy. Often times it was observed that several smaller casualties needed to slowly occur over time until the net negative effect on the system resulted in frequent alarms requiring the shut down and repair of the system. As described in the *Escanaba's* probe and controller casualty in Section 2.4.2.1, the combination of smaller casualties may complicate troubleshooting or hide a much larger problem.

It is clear from the analysis performed in this chapter that the NILM can be used to detect both minor and major casualties by simply looking at the power plot used by the system. As mentioned in the above chapter, research performed in this thesis diagnosed three major casualties that had been occurring without the crew's knowledge for an extended period of time. If the NILM data was made readily available to the crews all of these casualties and numerous smaller casualties would have been found and correctly within hours.

Although the NILM cannot often point directly to the real cause of the problem with 100% certainty, it can be used to notify the user of the errant behavior and can point you into the right direction. A synopsis of the NILM diagnostics applicable to power schedule analysis discovered in this chapter is listed below:

1. <u>Frequent Vacuum Pump Runs</u>: Frequent runs indicate a vacuum leak. During a low usage period during the night the pumps will cycle between 4 and 7 times an hour. During major leaks this number can increase to over 21 times per night with a much more regular interval between runs. (Section 2.4.3)
2. <u>Major Pressure Switch Casualties</u>: The average charge time for a single pump to increase system vacuum from 14-18" Hg is approximately one minute. If the pumps repeatedly run for time periods in excess of 3 minutes there may be an improperly set switch or extremely clogged pressure switch gauge line. (Section 2.2.2)
3. <u>Minor Pressure Switch Clogging</u>: A slow increase of single pump vacuum pump run time will occur as the pressure switch line becomes clogged. If the pumps run time increases slowly over time from 60 seconds to 80 or more seconds, there is a good indication of clogging in all smaller lines used by the pressure switch and pressure gauges. (Section 2.2.2.3)

4. Loss of Vacuum Pump Prime: This casualty results in a distinctive power plot characterized by the faulty vacuum pump not under load running for a long period until the backup pump kicks on and restores system pressure. These runs can last between 5-10 minutes. (Section 2.2.3)
5. Very Short or Very Long Discharge Pump Operation: This can either characterize a controller relay casualty, or a damaged/fouled level indicating probe. (Section 2.3.2)

Another important and valuable element that separates the NILM from current monitoring methods is the ability of NILM data to verify whether or not a repair was effective in solving the problem. In the case of the bad controller onboard the *Escanaba*, it proved the corroded probe was not all to blame for the errant discharge pump runs (Section 2.3.2.1). In the case of the check valve vacuum leak onboard the *Escanaba,* NILM data reassured the crew that the corrective actions taken were the correct ones to fix the problem (Section 2.4.3). This type of feedback provided during these casualties was invaluable to fault detection, correction, and subsequent verification of normal system operation.

3 Compressed Air Cycling System Diagnostics

3.1 Introduction

A NILM was installed to monitor the *Seneca's* Ship's Service Air Compressor in an attempt to expand research and collect data on as many new shipboard systems as possible. Unlike the CHT system, no power schedule data has been gathered by any other researcher in the NILM program's past. This system was chosen to be analyzed due to the limited amount of shipboard oversight associated with its automatic operation paired with the system's general likeness in principle to the CHT system. Both systems function to achieve a working system air pressure to accomplish vital shipboard auxiliary functions.

3.1.1 Basic System Information

Ship's Service Low Pressure Air is used onboard naval ships to power air-operated tools, the ship's whistle, and various air-actuated valves. Pneumatic tool hose connections and valves are located in several locations throughout the ship including work shops, machinery spaces, and weather decks while the ship's whistle is located on the ship's mast. The system consists of one electrical motor powering a belt-driven compressor. Pressure in the system is maintained between 90 and 120 psi by a pressure switch mounted to the side of the air receiver. This compressed air system can be cross connected into the ship's 225 psi Start Air system which is responsible for starting the ship's diesel engines, diesel generators, and operating the shaft air clutches in cases of emergency. Cross connection only occurs when one of the three compressors has failed. A basis system diagram can be seen in Figure 3-1 below:

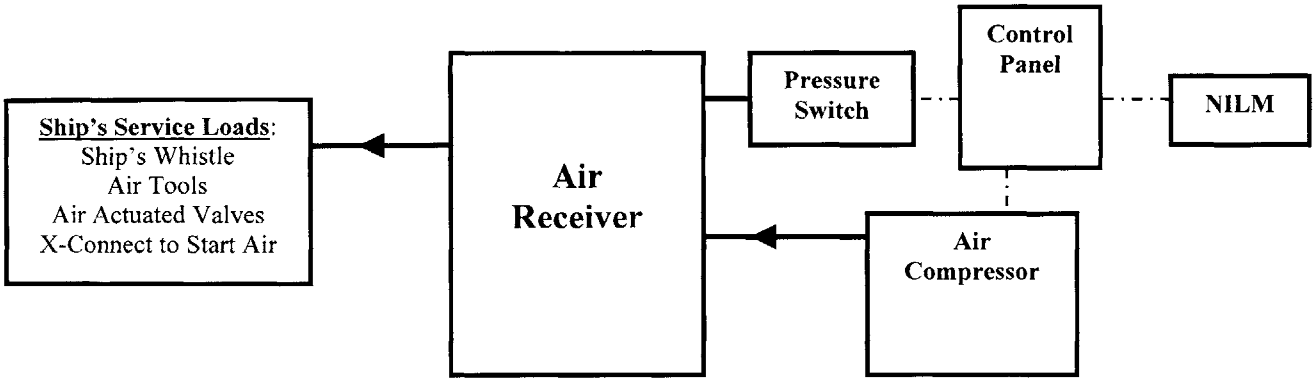


Figure 3-1: Basic system diagram of Low Pressure air system onboard 270' Famous Class Cutters

The operating schedule of the system's pneumatic loads is highly dependant upon conditions onboard the ship. Pneumatic tool usage is primarily limited to the work day hours between 0800 and 1600. The ship's whistle is only used occasionally with the exception of limited visibility weather conditions. When more loads are placed upon the system, the frequency of compressor operation will increase.

3.1.2 Shortcoming of Current Monitoring Methods

This system is more reliable than the CHT system due to its relative simplicity and cleanliness. As such, monitoring methods involve fewer checks and maintenance. A low pressure alarm is registered by the MCPMS system when the system pressure drops below 80 psi. Additional checks are made hourly by watch standers that check oil levels inside the compressor and the pressure inside the receiver tank. Condensation builds up in various low points in the system and these are evacuated once during every four hour watch.

The MPCMS low pressure alarm may repeatedly or continuously register a fault during periods of high system usage. During such cases the compressor may be unable to keep up with the load placed on the system causing receiver pressure to drop below 80 psi. These periods are usually limited to major work projects requiring several pneumatic tools or the ship's operation in fog or other cases when safe navigation requires long horn blasts. In these cases the alarm is monitored by watch standers and checks are made to ensure that the alarm does not persist any longer than it should.

The detection of small leaks is a much more difficult task. Because the system can keep up with these smaller leaks, no alarm is registered and a subsequent increase in operating frequency occurs without detection. These smaller leaks may occur for several reasons including pneumatic tool hoses that have not been properly secured, condensation blow down valves that have not been fully closed, or a casualties that have occurred at a pneumatic valve or fitting. Similar to the vacuum leaks in the CHT system, the audible hiss of escaping air is often drowned out by other shipboard systems. This unneeded increase in usage that can be detected and prevented by the NILM.

3.2 NILM Diagnostic Software

The compressed-air system is much simpler than the CHT system due to the fact that only one cycling load is being monitored. This relative simplicity makes the creation and application of diagnostic software much easier. Such software was developed and applied the system and an example of outputs available from the monitoring software can be seen in the following figures. In this case a moderate leak in the form of a slightly cracked blow down valve was imposed on the system for three hours at the end of the work day.

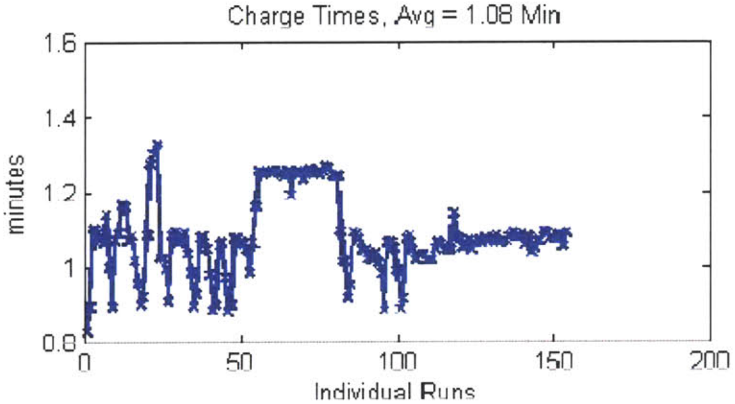


Figure 3-2: This plot depicts the length of each run of the *Seneca's* compressor for 150 runs that occurred over 23 hours. The step increase in run time indicates a 3 hour period where a moderate leak was imposed on the system.

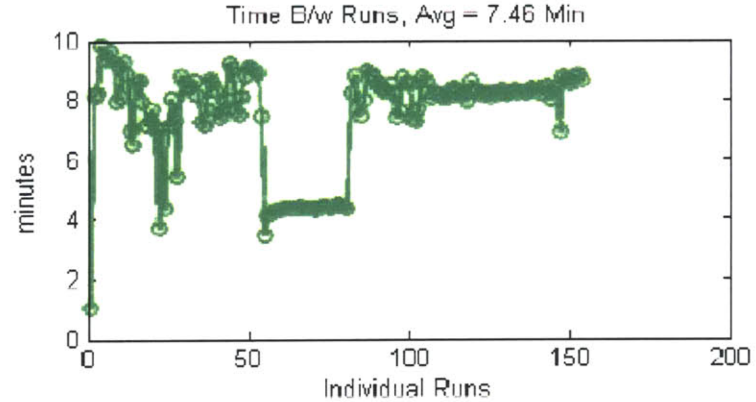


Figure 3-3: This plot depicts the "OFF" time period between the 150 runs over 23 hours onboard the *Seneca*. The step decrease in time between runs indicates the three hour leak period.

Each plot shows the detailed information gathered by the diagnostic software. In this case, an open air valve caused a sharp increase in the length of operation paired with a sharp decrease in the time between compressor runs. This information provides immediate feedback to watch standers as to the presence of a leak in order to prompt troubleshooting efforts. If no feedback occurs, troubleshooting could be delayed for extended periods of time allowing unneeded usage to occur. Additional administrative analysis could also be provided by this software to provide overall usage over a period of time. For instance, Figure 3-4 documents each hour's total operation while calculating total system usage over 23 hours. This data can provide the detailed information needed to enable more specific time frames for preventative maintenance. Current preventative maintenance procedures for cycling systems usually focus on generic time frames rather than on more specific information based on actual operation.

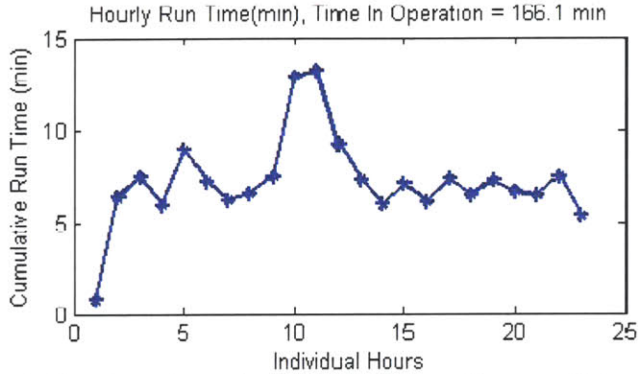


Figure 3-4: Hourly total run times and total operation over 23 hours. The hump in total operation for those hours coincides with simulated cracked valve casualty.

3.3 Ship's Whistle Leak

Only one documented case of a major casualty has been recorded by the NILM. This case involved a blown seal on the *Seneca's* ship's whistle that was only detected when the ship sounded the horn during navigation detail on return to homeport. Investigation of a weak and odd sounding horn blast resulted in the detection of a weathered and cracked seal noisily hissing air out of the system. Examination of the 35 days of data surrounding the leak indicated a distinct drop in the number of compressor starts per hour after the ship's whistle had been corrected. The total number of starts occurring between 0000 and 0400 was recorded each night and plotted in Figure 3-5.

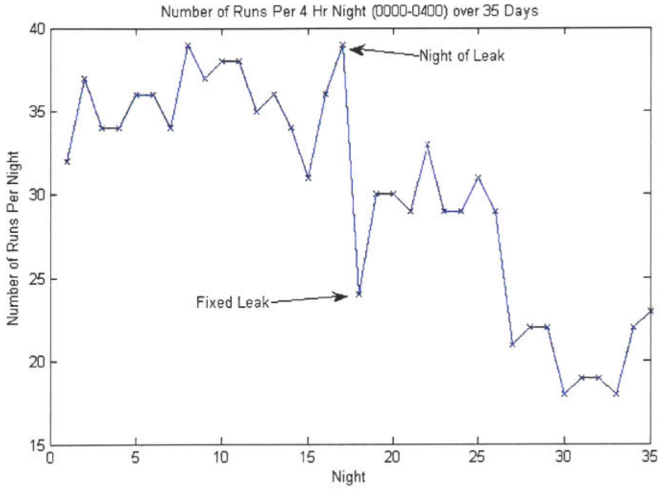


Figure 3-5: Total number of compressor starts occurring between 0000 and 0400 for the 35 days surrounding the *Seneca's* ship's whistle leak.

Just knowing the basic operation schedule of the system would allow the ship's crew to quantify the effect of a repair on the overall usage of the system. Other instances of highly excessive usage have been recorded by the NILM. Figure 3-5 records a leak of unknown origin. For comparison purposes, the top plot depicts a normal four hour period when system usage is at a minimum from 0000- 0400. During these times of low usage the compressor charges the receiver anywhere from 3 to 5 times an hour. The bottom plot depicts the same time frame with a 300-400% increase in the frequency of usage due to an unknown leak. This casualty hadn't been recorded by the crew and was probably a result of an improperly closed valve

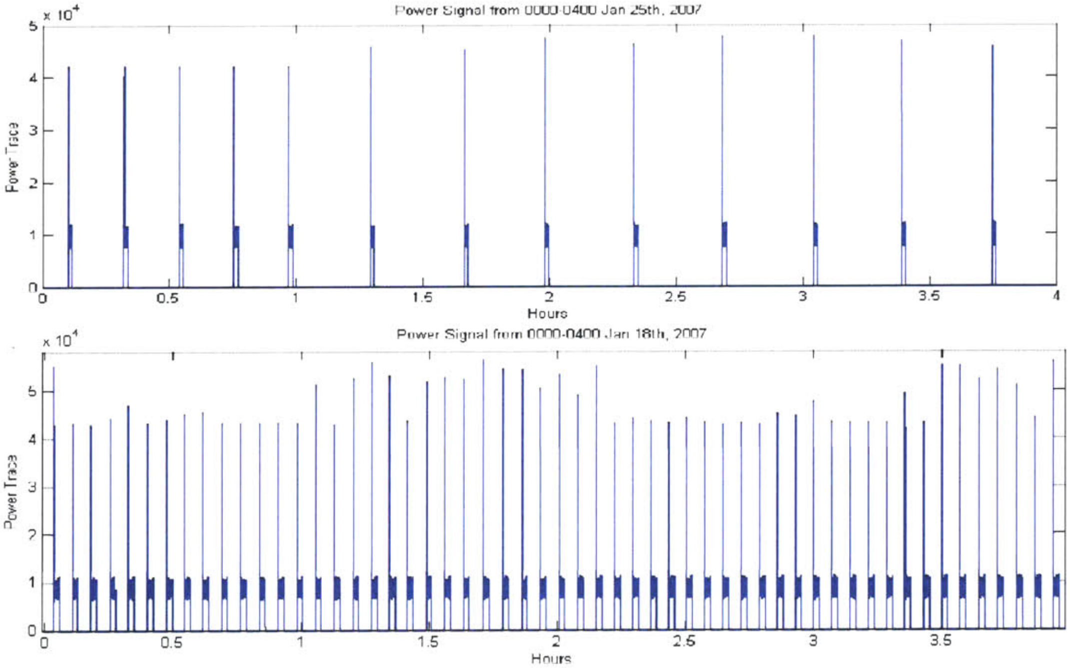


Figure 3-6: Normal four hour period of compressor operation (top); Large leak condition during the same time frame (bottom)

3.4 Compressed Air Cycling System Conclusion

Current monitoring processes employed Ship's Service Air system completely neglects casualties not resulting in system failure. The analysis of this system proves that the NILM would be able to automatically analyze a system to provide a range of output parameters. Quantifiable increases in operation can prompt personnel to search for open valves or leaks while quantifiable decreases in operation can confirm the actions they had taken to correct the problem had worked. This sort of observation provided by the NILM could only be provided by a dedicated watch stander logging total operation of each piece of equipment using current monitoring practices.

4 Ventilation Fan Overhaul

4.1 Introduction

The research presented in the first three chapters of this thesis went into depth describing the ability of the NILM to monitor cycling systems. Those systems automatically switch on and off and any deviations from normal operating schedules can be correctly diagnosed and prevented. Steady-state systems that are set to run continuously for long periods of time require a different type of analysis. To assess the NILM's ability to monitor these systems, experiments and analysis of a vane axial ventilation fan were performed before and after a major overhaul.

4.1.1 Basic System Information

The ventilation fan in question is one of two fans responsible for ventilating the Auxiliary Machine Space. One fan serves as a supply ventilation fan while the other serves an exhaust fan. Both fans are of the same capacity and operate at two different fan speed settings. Control of these fans can be achieved in the main control space and locally at the panel. These fans operate constantly to provide ventilation to this space and alignment of ventilation is only changed occasionally in response to changing seasonal temperatures and heat loads associated with underway operation. A diagram summarizing the system can be seen in Figure 4-1.

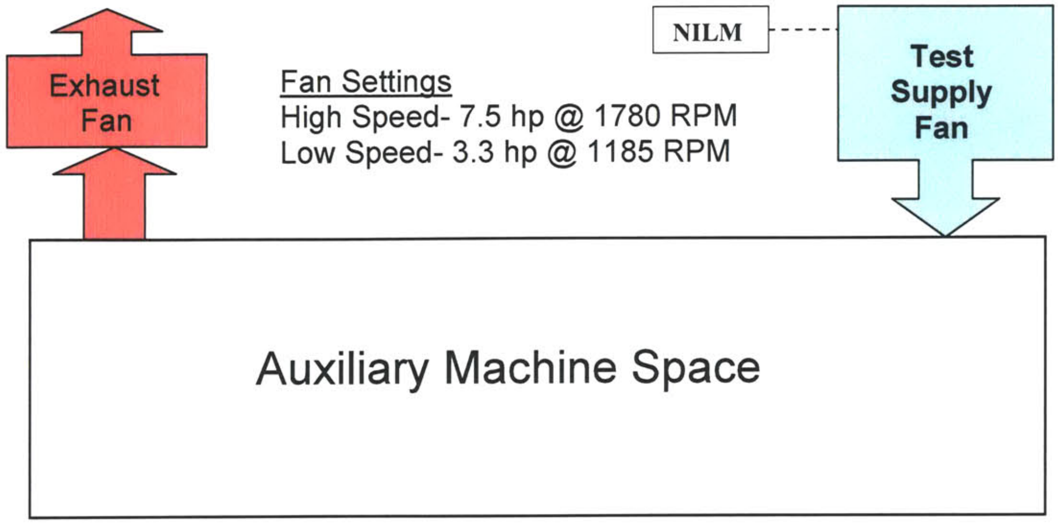


Figure 4-1: Basic ventilation fan diagram and parameters.

4.1.2 *Current Monitoring Methods*

While in port the *Escanaba* and the *Seneca* are supported by maintenance units located at the Coast Guard Base in Boston. These units perform less frequent maintenance procedures that range from major engine overhauls to more technical procedures that require special training. To determine the health of the ventilation fans onboard the ships, a vibration analysis is performed by the electrical shop on base. This vibration analysis is performed using the hand held DLI Watchman ST-101 vibration analyzer [24] that quantifies the amount of vibration at different frequency ranges. Although this method is crude in comparison to the larger scale vibration analysis tools used by the Navy, it still provides a good basic indication of fan imbalance. On the cutters this analysis is not regularly scheduled and results are only recorded in order to indicate persistent excessive vibrations that would require an overhaul.

4.2 Data Collection Procedure

The intent of the analysis was to determine if power data could be used to detect or diagnose any important failures of faults. As an initial experiment, a NILM was temporarily installed both before and after an overhaul. A set of tests combining several different fan speed alignments was completed in an attempt to determine the effect of supply/exhaust fan alignment on the system. A tarp was used to achieve 0%, 50%, and 80% blockage to test the effect of supply fan intake blockage. Fifteen total combinations were completed by varying fan speed ventilation and percentages of blockage. For safety purposes data was not collected at high speed for 80% blockage. Table 4-1 summarizes the data collection process and fan settings for the 15 separate tests performed prior to the fan overhaul.

Table 4-1: Outline of all tests performed before the fan overhaul. All tests were duplicated in the same process after the overhaul as well. All similar tests were compared.

Zero Supply Blockage			**50% Supply Blockage**			**80% Supply Blockage**		
Supply	**Exhaust**	**Name**	**Supply**	**Exhaust**	**Name**	**Supply**	**Exhaust**	**Name**
High	High	Fan_1	High	High	Fan50_1	High	High	*not completed
High	Low	Fan_2	High	Low	Fan50_2	High	Low	*not completed
High	Off	Fan_3	High	Off	Fan50_3	High	Off	*not completed
Low	High	Fan_4	Low	High	Fan50_4	Low	High	Fan80_4
Low	Low	Fan_5	Low	Low	Fan50_5	Low	Low	Fan80_5
Low	Off	Fan_6	Low	Off	Fan50_6	Low	Off	Fan80_6

Due to the temporary and exploratory nature of this initial monitoring project, power data was only obtained during the low speed tests. Additionally, the scaling data needed to convert NILM measurements into the appropriate units (i.e. Watts and VAR's) was not obtained. All data presented in this chapter, however, can be appropriately scaled if several more experiments are performed. Regardless, the lack of scale factor does not affect the accuracy of the data or the resulting conclusions.

4.3 Ventilation Fan Test Results

4.3.1 Alignment and Blockage Results

Different combinations of supply/exhaust fan alignments were examined to see how internal system pressure affects the supply fan. When the exhaust ventilation is off, the supply fan is working harder against back pressure in the space. Similarly when the exhaust ventilation is off and the supply is on low, a different operating pressure can be achieved. As shown in this section, power data does not indicate much about such changes.

The intake blockage portion of the experiment demonstrates the irresponsive nature of the electrical power to ventilation alignment. In all tests there was no change in power drawn between the 0% and 50% blockages at the intake. At 80% blockage, however, a 10% decrease in power drawn was observed in the low speed steady state power. One set of tests showing this behavior can be seen in the figures below.

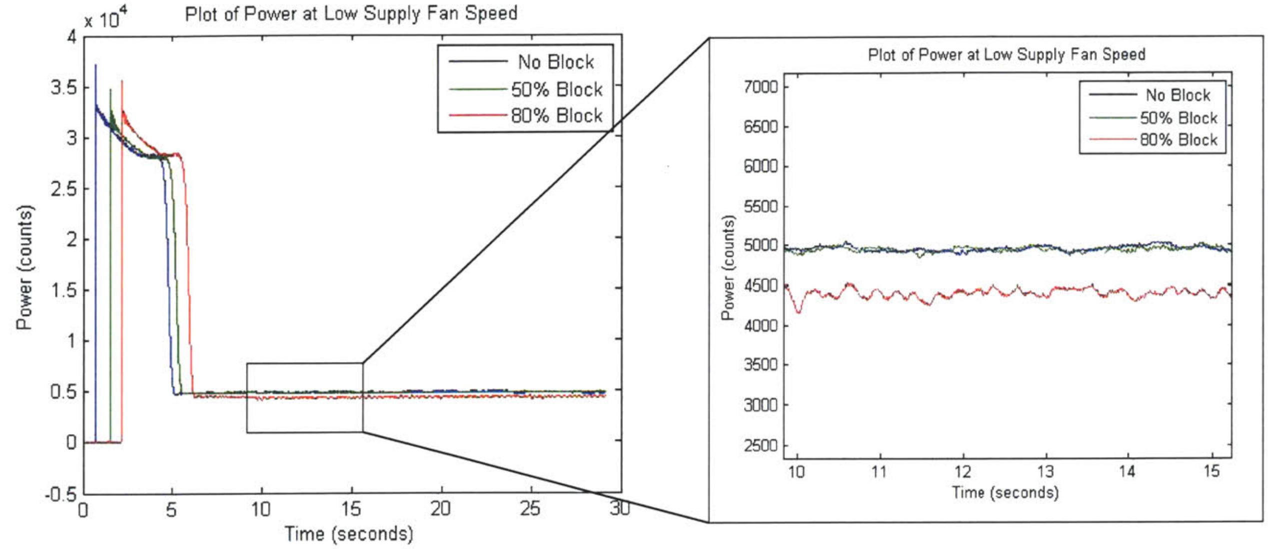


Figure 4-2: Plot of supply fan power with 0%, 50%, and 80% blockage at intake. Note the 10% decrease in power drawn during the 80% blockage case.

Figure 4-3 records the irresponsive nature of the power drawn during the nine tests performed at low speed with varying blockages and speed alignments. These tests indicate that no noticeable change in supply fan power occurs until almost 80% blockage is achieved at the intake. Additionally, the irresponsiveness of the fans to the alignment makes the NILM an unreliable method of determining slight changes in intake due to the nature of the system.

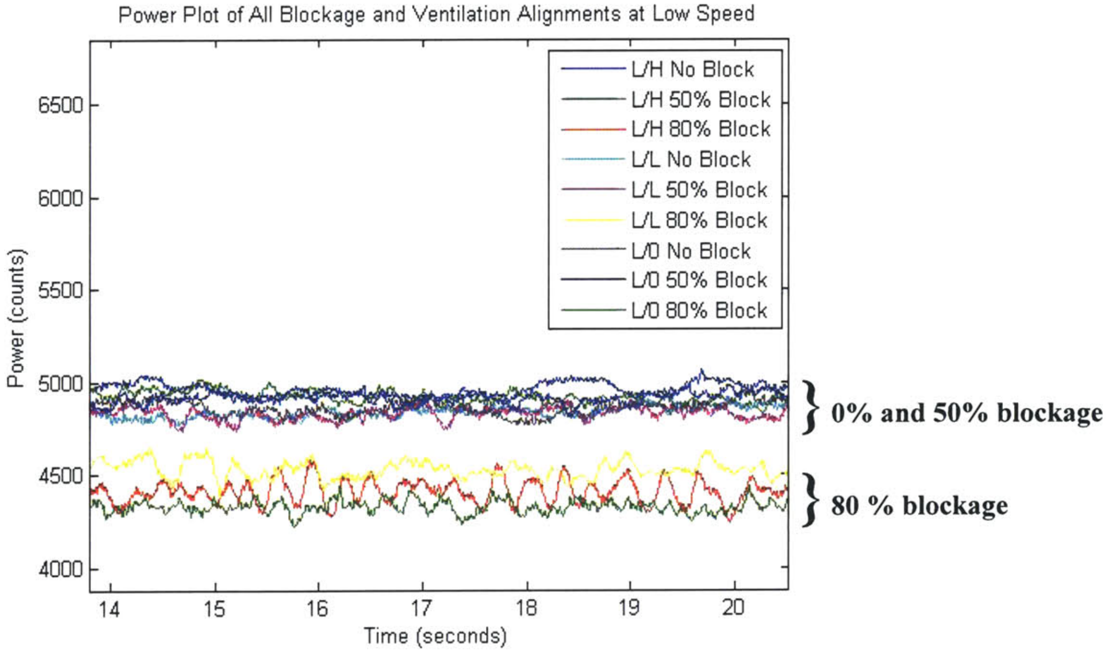


Figure 4-3: Zoomed in steady state power data for all 9 tests completed at low speed.

These tests indicate that no noticeable change in supply fan power occurs until almost 80% blockage is achieved at the intake. Additionally the irresponsiveness of the fans to the alignment makes the NILM an unreliable method of determining slight changes in intake due to the nature of the system.

4.3.2 Frequency Content Analysis

The frequency content of the fan was also analyzed during steady state operation to determine if changes in fan vibration could be correlated to the overhaul of the fan. A Fast Fourier Transform (FFT) was used to examine the frequency content of the power. The frequency spectra were examined both before and after the overhaul. The spectrum corresponding to the real power content (P) showed no direct change before and after the overhaul, while the reactive power (Q) showed a distinct drop in the magnitude at 40Hz in all similar tests before and after the overhaul. An example of this can be seen in Figure 4-4.

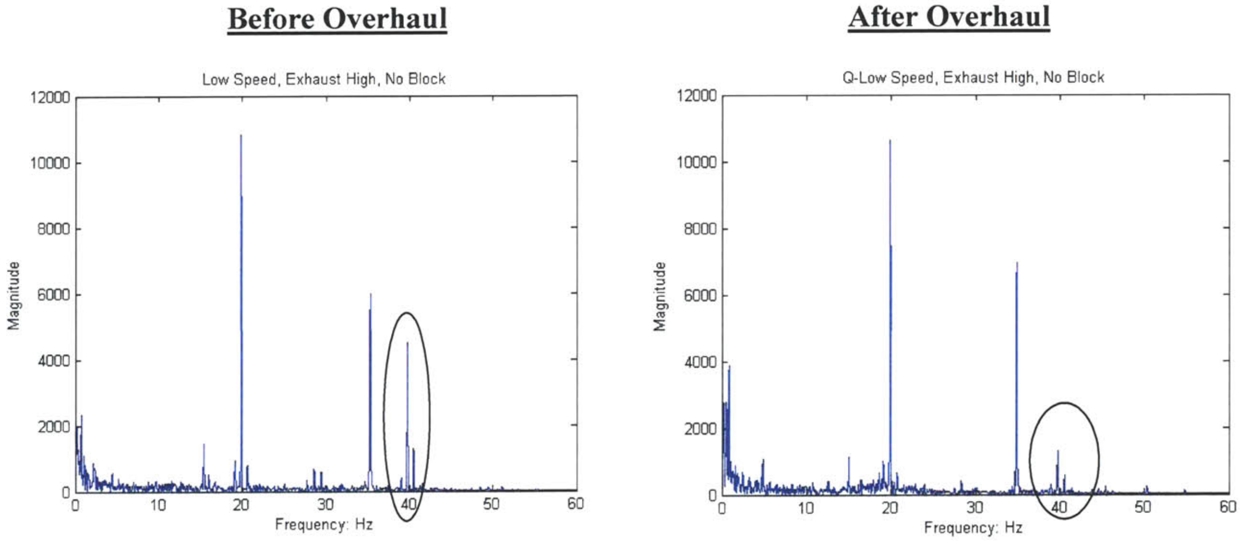


Figure 4-4: Plot of reactive power (Q) frequency content. The drop in magnitude of the 40hz spike occurred in all tests at the low speed setting.

The fan overhaul included a complete cleaning with a bearing renewal. This overhaul could have resulted in the decrease in the magnitude of frequency content in the 40Hz range. Because the high speed data did not include power data prior to the overhaul, no comparison can be made at this speed.

4.4 Vane Axial Fan Conclusion

The data collected during this evaluation of the system provides a brief look into the potential of detecting fan imbalance and loading using the NILM and supporting software. This ability would be a valuable tool that could be used to quickly determine the bearing health of a system from a remote location. Although these results seem promising, no real conclusion can be drawn as to the real ability of the NILM to detect these faults until similar results are reproduced in further research.

5 Future Work and Conclusion

The non-intrusive load monitor clearly has the potential to simplify shipboard maintenance. This potential is strengthened by the fact that a single NILM can clearly provide useful diagnostic information about multiple loads. This capability means that it may be possible to enhance the performance of systems such as ICAS or MPCMS without having to add many new sensors.

Although the NILM has already been used to monitor several downstream loads, the next step in research is to press for an even less intrusive alternative. Ongoing efforts should be aimed at increasing the load monitoring capacity to include several systems at once from a single point. This is most closely modeled by the CHT monitoring system but should be expanded to include several auxiliary systems at once.

List of References

[1]. DiUlio, M., C. Savage, B. Finley, and E. Schneider. 2003. Taking the integrated condition assessment system into the year 2010. In Proc. 13th Ship Control Symposium, Orlando, FL.

[2]. Lopushansky, R. 1999. All optical shipboard sensing system. In *Proc. 45th International Instrumentation Symposium,* May, Albuquerque, NM.

[3] Leeb, S., S. Shaw, and J. Kirtley. 1995. Transient event detection in spectral envelope estimates for nonintrusive load monitoring. *IEEE Trans. on Power Delivery* 10: 1200–1210.

[4] Shaw, S. 2000. System identification techniques and modeling for non-intrusive load diagnostics. Ph.D. diss., Massachusetts Institute of Technology, Cambridge.

[5] DeNucci, T. et al. 2005. Diagnostic indicators for shipboard systems using non-intrusive load monitoring. In *Proc. 1st IEEE Electric Ship Technologies Symposium*, July, Philadelphia, PA.

[6] Cox, R., J. Mosman, T. McKay, S. Leeb, and T. McCoy. 2006. Diagnostic indicators for shipboard cycling systems using non-intrusive load monitoring. In *Proc. ASNE Day 2006*, June, Arlington, VA.

[7] Cox, R., P. Bennett, T. McKay, J. Paris, and S. Leeb. 2007. Using the non-intrusive load monitor for shipboard supervisory control. To appear in *Proc. 2nd IEEE Electric Ship Technologies Symposium*, May, Arlington, VA.

[8] Mitchell, G., R. Cox, J. Paris, and S. Leeb. 2007. Shipboard fluid system diagnostic indicators using non-intrusive load monitoring. To appear in *Proc. ASNE Day 2007*, June, Arlington, VA.

[9] Shaw, S., C. Abler, R. Lepard, D. Luo, S. Leeb, and L. Norford. 1998. Instrumentation for high performance nonintrusive electrical load monitoring. *ASME Journal of Solar Energy Engineering* 120: 224-229.

[10] Oppenheim, A., A. Willsky, and I. Young. 1988. *Signals and Systems.* Englewood Cliffs, NJ: Addison Wellesley.

[11] Lee, K. 2003. Electric load information system based on non-intrusive power monitoring. Ph.D. diss., Massachusetts Institute of Technology, Cambridge.

[12] Cox, R. 2006. Minimally intrusive strategies for fault detection and energy monitoring. Ph.D. diss., Massachusetts Institute of Technology, Cambridge.

[13] Armstrong, P., C. Laughman, S. Leeb, and L. Norford. 2006. Detection of rooftop cooling unit faults based on electrical measurements. *HVAC+R Research Journal* 12: 151–175.

[14] Cox, R., P. Bennett, T. McKay, J. Paris, and S. Leeb. 2007. Using the non-intrusive load monitor for shipboard supervisory control. To appear in *Proc. 2nd IEEE Electric Ship Technologies Symposium*, May, Arlington, VA.

[15] Luo, D. 2001. Detection and diagnosis of faults and energy monitoring of HVAC systems with least- intrusive power analysis. Ph.D. diss., Massachusetts Institute of Technology, Cambridge

[16] Laughman, C., P. Armstrong, L. Norford, and S. Leeb, 2006. The detection of liquid slugging phenomena in reciprocating compressors via power measurements. In *Proc. International Compressor Engineering Conference at Purdue*, July, West Lafayette, IN.

[17] Paris, J. 2006. A framework for non-intrusive load monitoring and diagnostics. M.Eng. thesis, Massachusetts Institute of Technology, Cambridge.

[18] T.W. DeNucci. "Diagnostic Indicators for Shipboard Systems using Non-Intrusive Load Monitoring," Massachusetts Institute of Technology S.M. NAME/S.M. ME Thesis, June 2005.

[19] J.S. Ramsey, Jr. "Shipboard Applications of Non-Intrusive Load Monitoring", Massachusetts Institute of Technology NSEE/S.M. EECS thesis, June 2004.

[20] J.P. Mosman "Evaluation of Non-Intrusive Load Monitoring for Shipboard Cycling System Diagnostics," Massachusetts Institute of Technology NE/S.M thesis June 2006.

[21] Instruction Manual for the Envirovac Vacuum Sewage Collection System, United States Coast Guard 270' B Class WMEC. Technical Publication No. 2839

[22] Saunders, Stephen, ed. Jane's Fighting Ships, 2002-2003. Alexandria, 2002.

[23] Cox, R,. M. Piber, G. Mitchell, P. Bennett, J. Paris, W. Wichakool, S. Leeb, 2007. *Improving Shipboard Maintenance Practices Using Non-Intrusive Load Monitoring*. In *Proc. of ASNE Intelligent Ships Symposium VII*, Philadelphia, PA, May 2007

[24] DLI Watchman ST-101 Vibration Screening Tool Online Operator's Guide. http://www.spintelligentlabs.com/SL-docs/st-101-og-flat.pdf 15 May 2007